Evaluating Admittance Relaying for Inverter-Interfaced Microgrid Protection

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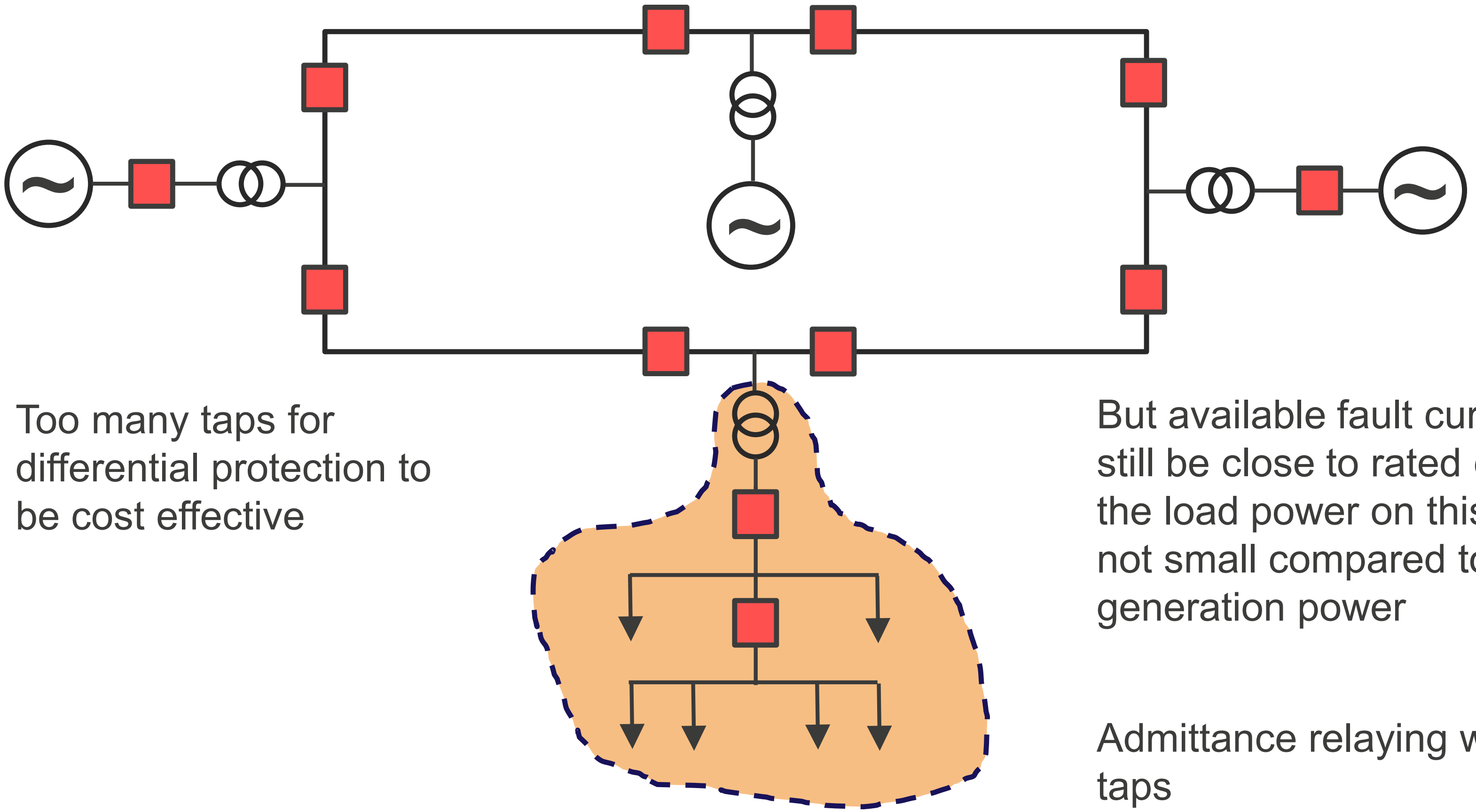
Microgrid Protection Challenges

- **Protection Difficulties**
  - Low fault current provided by inverter-interfaced generation
  - Bidirectional flow of fault current
  - Meshed lines
  - Many taps compared to transmission
  - Connect and disconnect to the main electrical grid, changing the fault current
  - Must avoid disconnecting local generation in case islanding is necessary

- **Current Best Practice**
  - Overcurrent relaying with negative and zero sequence current, time-overcurrent backup
  - Cons: false tripping if load imbalance is high (> 20%), poor response time for balanced faults

Why Not Use Differential Protection Everywhere?



Too many taps for differential protection to be cost effective

But available fault current can still be close to rated current if the load power on this bus is not small compared to total generation power

Admittance relaying works with taps

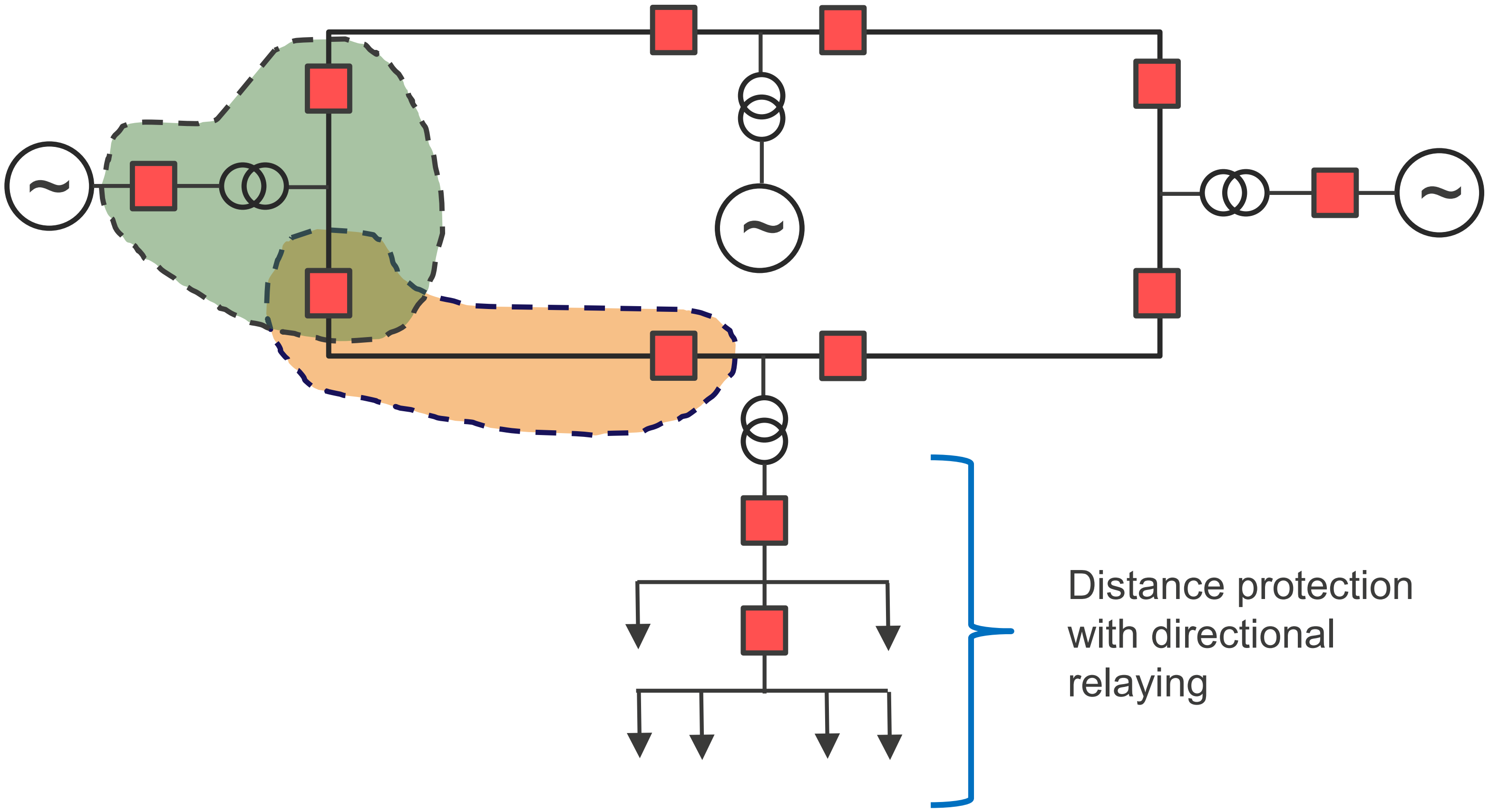
Some Fixes

- **One possible solution is to provide fault current via rotating equipment, eg. Synchronous condensors or induction motors**
- **Downsides: fault current really isn’t desirable as it can cause damage to equipment**
- **Although fault current isn’t present, this is an easier problem than trying to detect high-impedance faults**
- **More possible solutions: look at transmission system protection**
    - Traveling-wave protection
    - Distance protection
    - Differential protection
    - Pilot protection

Current State of the art in Microgrid Protection

- **CERTS microgrid: use negative-sequence and zero-sequence directional overcurrent protection**
- **Problems:**
  - Potential for load encroachment if load is unbalanced. This could occur if protection on a single-phase circuit trips, causing an upstream trip
  - Cannot detect bolted three-phase faults. While a small fraction of faults, these are not rare

How About Admittance Protection?

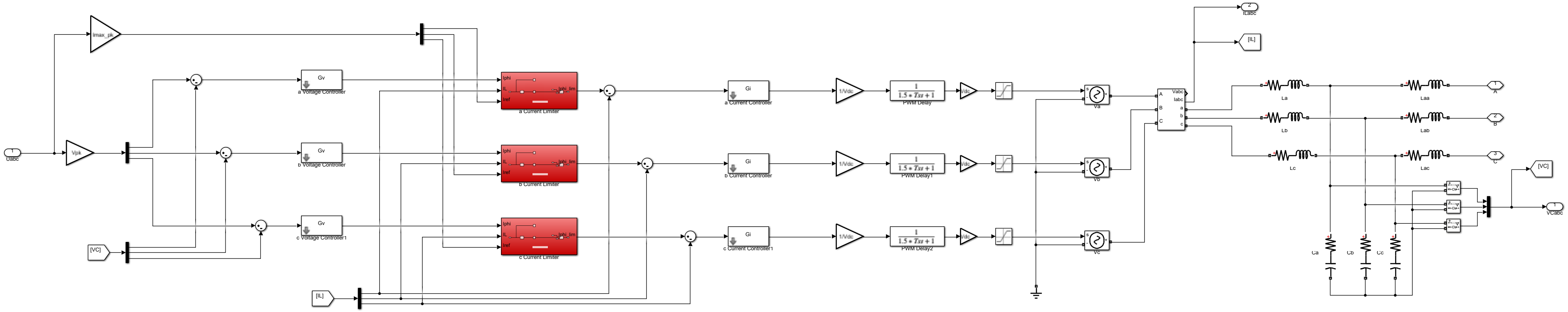


Distance protection with directional relaying

Microgrid Converter Design

Controller

Infinite-switching frequency model of Power Stage



Voltage Controllers

Current Limiters

Current Controllers

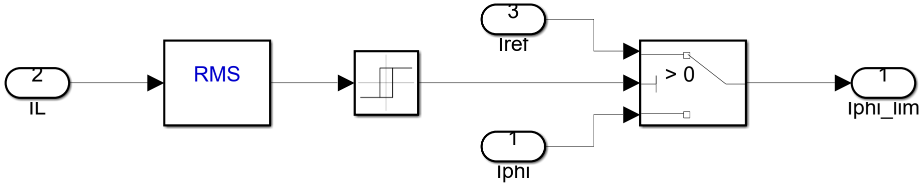
PWM Delay & Voltage limits

Sinusoidal Voltage sources

LCL output filter

Microgrid Converter Controller Design

- PR controllers offer better performance during unbalanced operation and in the presence of load harmonics compared with proportional-integral (PI) controllers in a rotating reference frame (eg. DQ0).
- Static reference frames include the Clark (αβγ) and ABC coordinates.
- ABC coordinates require 3 sets of controllers instead of 2 but avoid difficulties with voltage regulation on the healthy phase during unbalanced faults.



Latched current limiters as opposed to instantaneous saturation avoid harmonic injection during faults but introduce can introduce a current discontinuity when switching the current controller reference from the voltage controller output to the limited current signal

Admittance Protection in More Detail

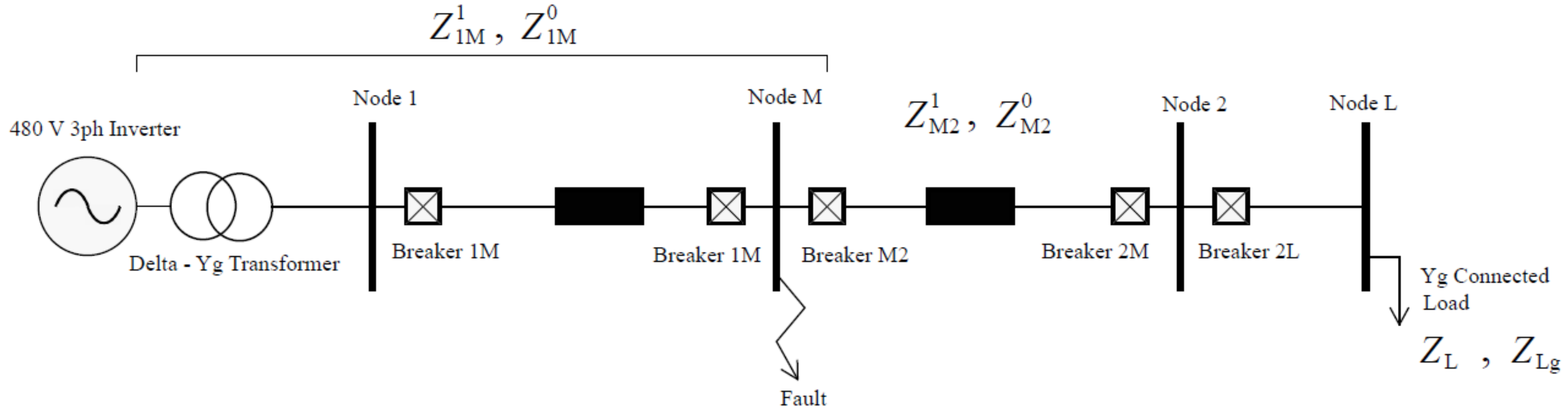
- **Ground Fault Protection**
  - Use estimate of Z1 behind the relay (why not use V0/I0? We'll get to that…)
  - Use current compensation

$$\boldsymbol{Z_{1eq} = \frac{V_a}{I_a + KI_0}}$$

- **Line Fault Protection**

$$Z_{LL} = \frac{V_a - V_b}{I_a - I_b}$$

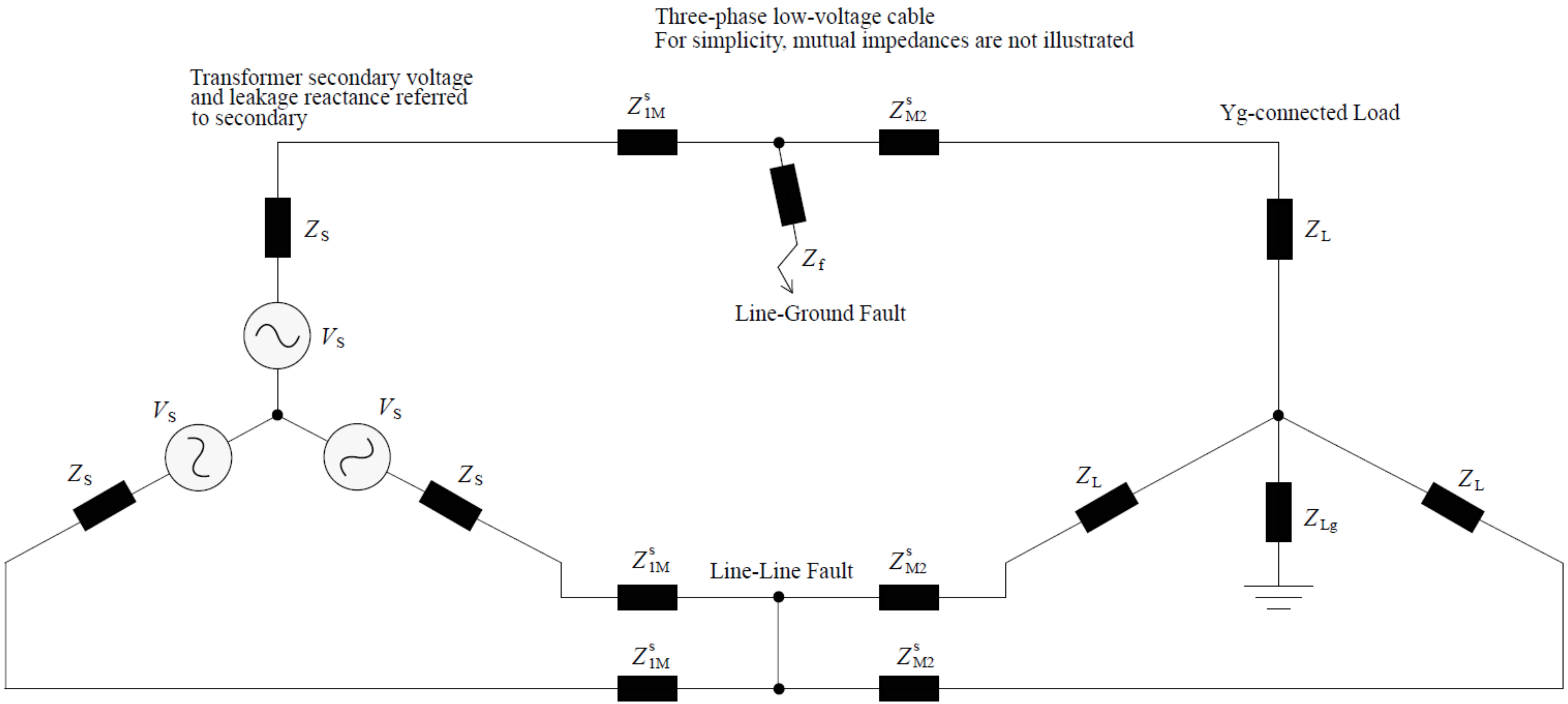
Case Study System Oneline



- *S. Kar and S. R. Samantaray, "Time−frequency transform−based differential scheme for microgrid protection," Transmission Distribution IET Generation, vol. 8, no. 2, pp. 310−320, 2014.*
- *M. Dewadasa, A. Ghosh, and G. Ledwich, "Line protection in inverter supplied networks," in 2008 Australasian Universities Power Engineering Conference, 2008, pp. 1−6*
- *N. El Halabi, M. García−Gracia, J. Borroy, and J. L. Villa, "Current phase comparison pilot scheme for distributed generation networks protection," Applied Energy, vol. 88, no. 12, pp. 4563−4569, 2011.*

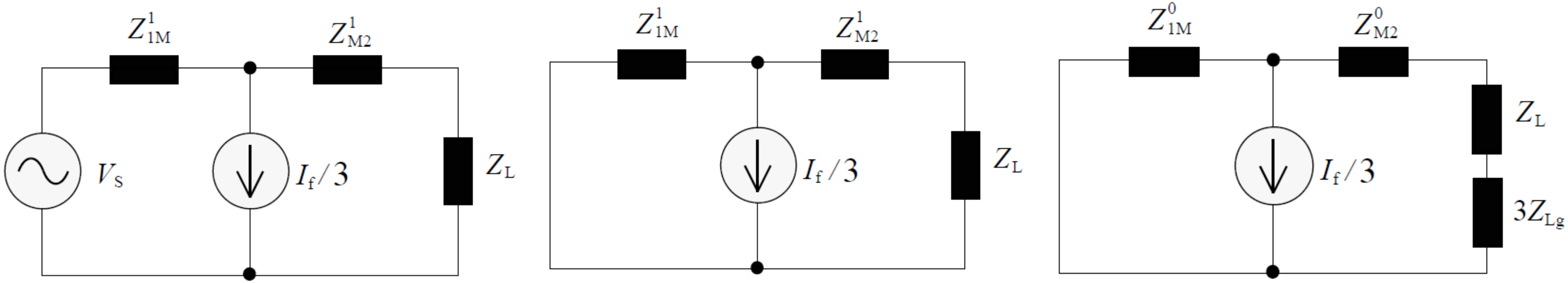
Name	Symbol	Value	Unit
Inverter rated power	P	50	kW
DC-bus voltage	Vdc	1800	V
Output filter inductance	L	18	μF
Output filter capacitance	C	250	nF
Maximum rms output current	Imax	70	A
Cable resistance	Rc	39	mΩ
Cable inductance	Lc	70.8	μH
Load real power	Pd	25	kW
Load reactive power	Qd	12.5	kW

Case Study System in Detail



Today we'll just look at behavior under line-ground faults

Sequence Analysis: Equivalent Sequence Networks & Sources

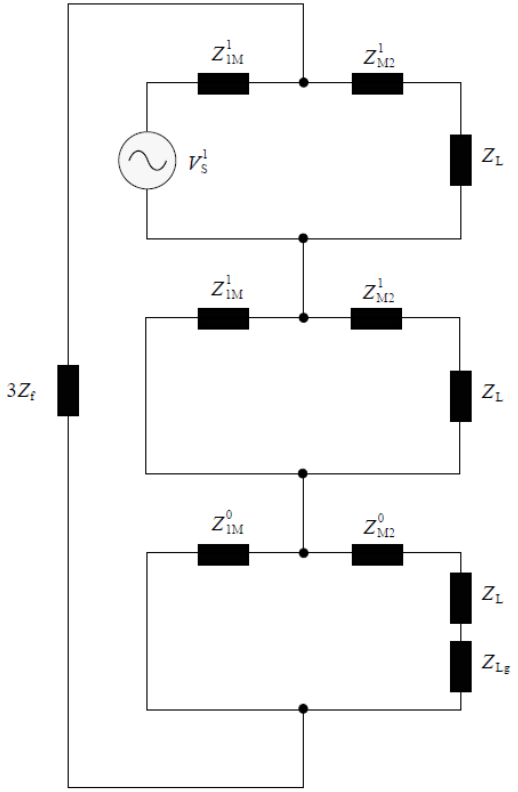


(a) Equivalent positive-sequence network (b) Equivalent negative-sequence network (c) Equivalent zero-sequence network

Note that $I^0_{af} = I^1_{af} = I^2_{af} = \frac{I_f}{3}$

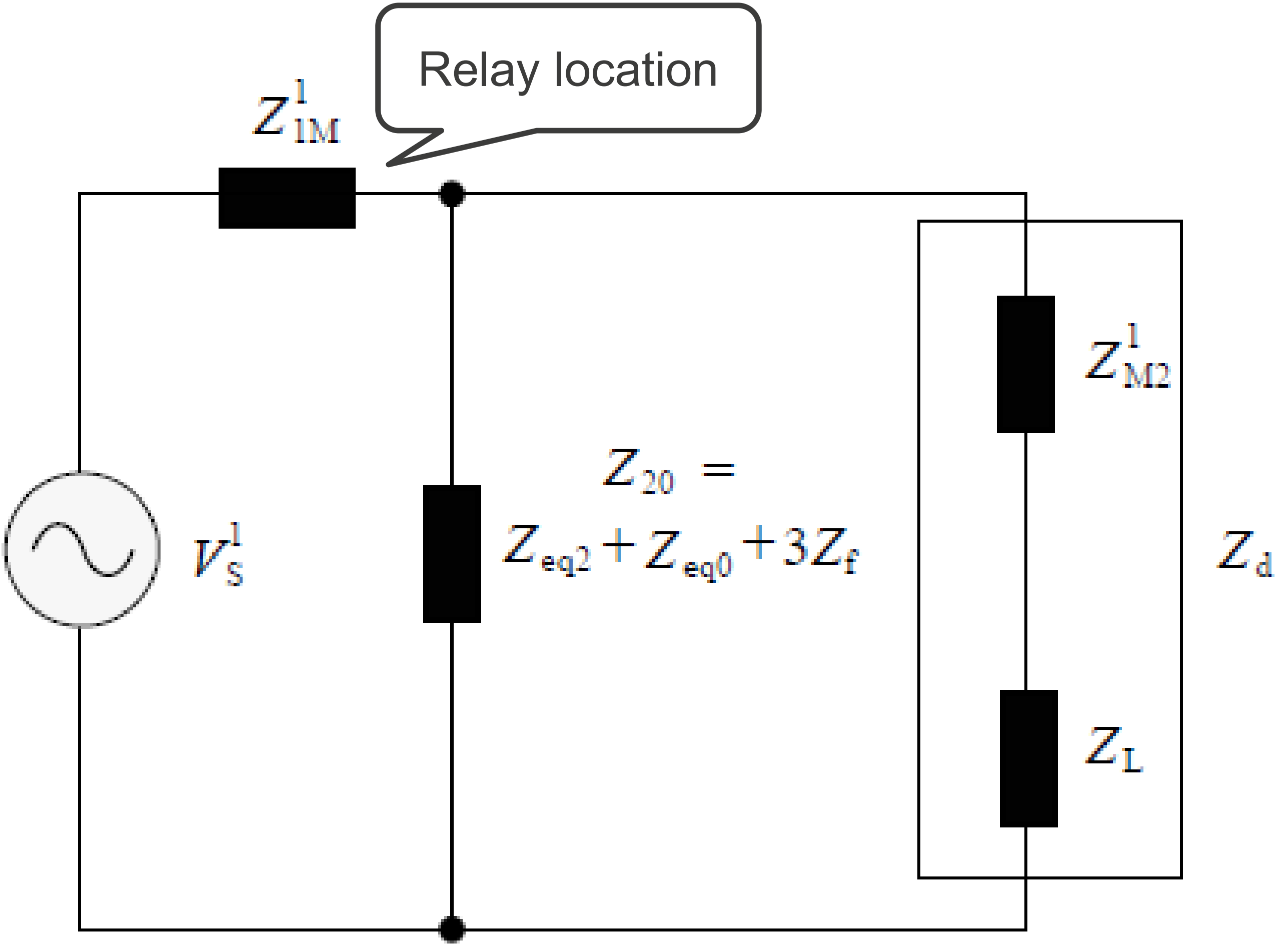
$$\begin{bmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} I_a \\ I_a \\ I_a \end{bmatrix}$$

Sequence Analysis: Join the Sequence Networks Together

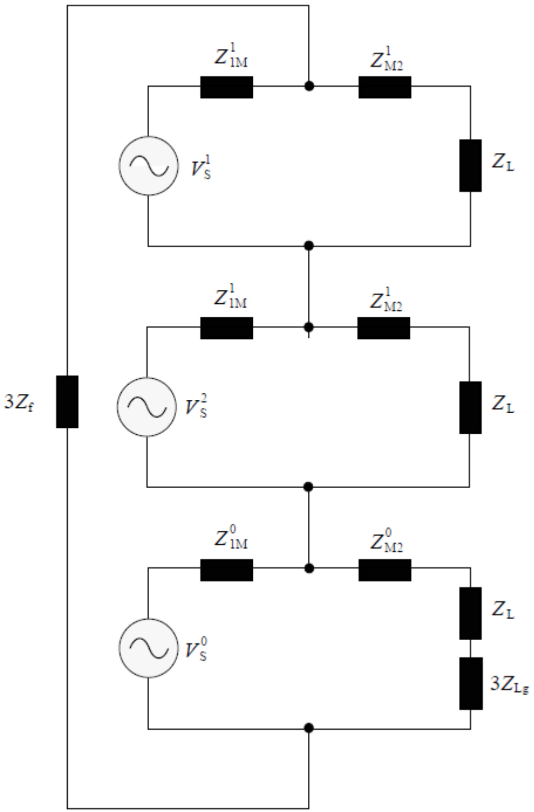


Because $I^0_{af} = I^1_{af} = I^2_{af}$, this justifies a series interconnection of the networks

Sequence Analysis: Simplify the Network



Sequence Analysis: Unbalanced Case



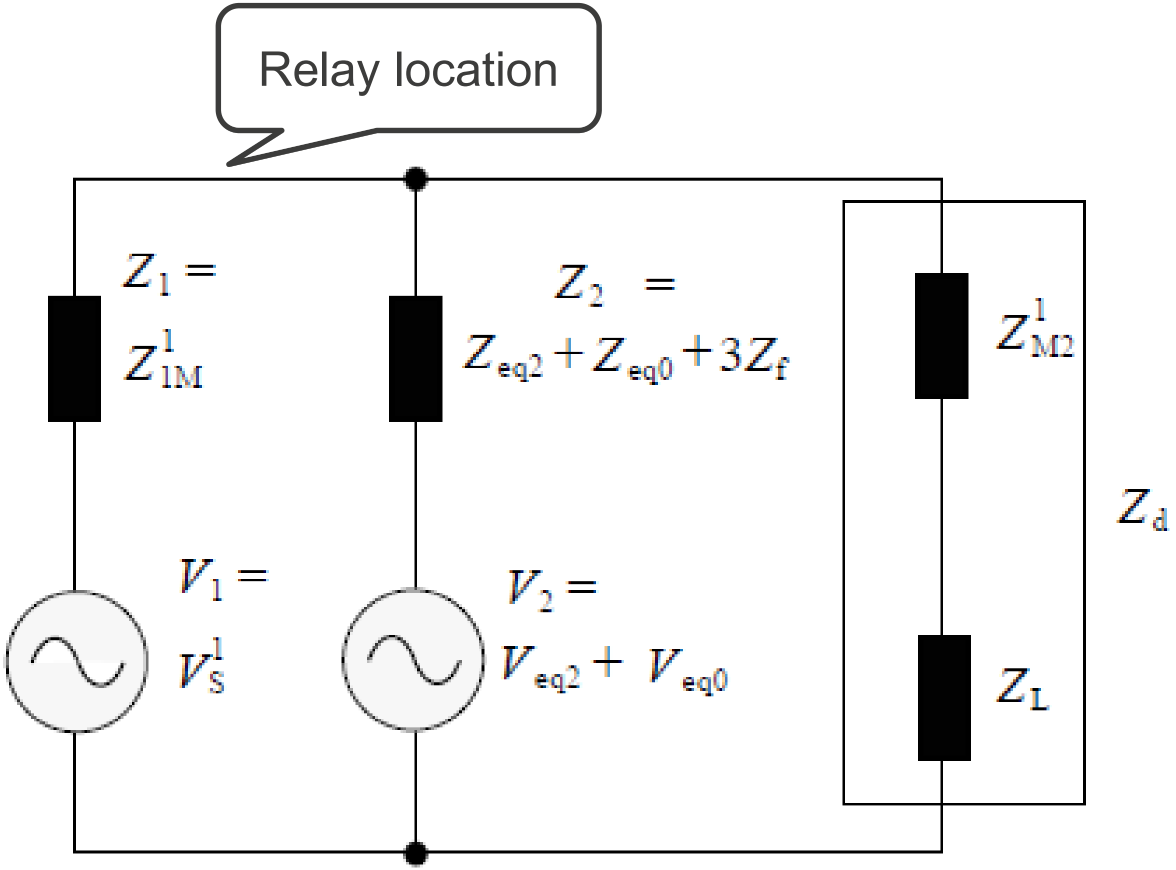
- **Limiting the current on the faulted phase of the inverter can be approximated as reducing the voltage**
- **This results in nonzero zero- & negative-sequence voltages at the source**

$$\begin{bmatrix} V_{ag}^0 \\ V_{ag}^1 \\ V_{ag}^2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_f \\ \alpha^2 V_s \\ \alpha V_s \end{bmatrix}$$

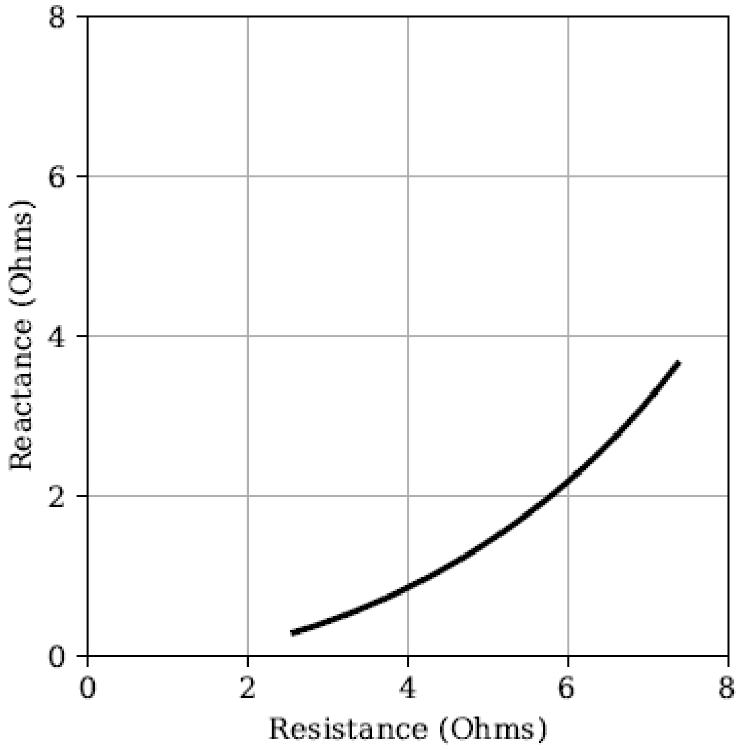
$$= \frac{1}{3} \begin{bmatrix} V_f + \alpha^2 V_s + \alpha V_s \\ V_f + \alpha^3 V_s + \alpha^3 V_s \\ V_f + \alpha^4 V_s + \alpha^2 V_s \end{bmatrix}$$

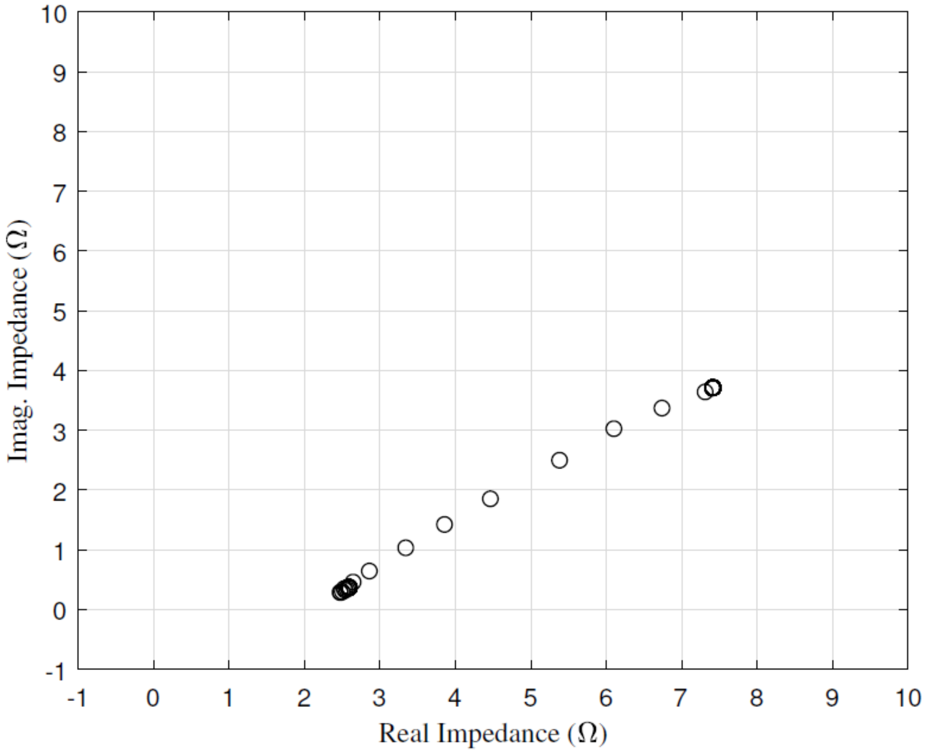
$$= \frac{1}{3} \begin{bmatrix} V_f + (\alpha^2 + \alpha) V_s \\ V_f + 2V_s \\ V_f + (\alpha^2 + \alpha) V_s \end{bmatrix}.$$

Sequence Analysis: Simplify the Network for the Unbalanced Case



Measured & Simulated Impedance for Downstream Line-Ground Fault





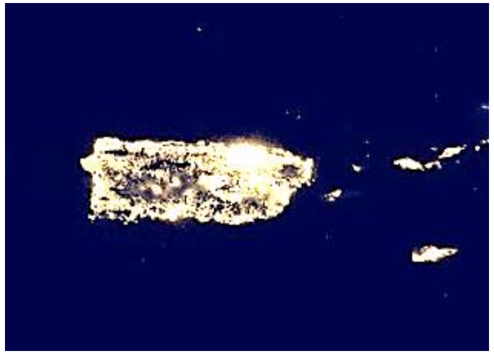
Conclusions

- **Admittance protection with current compensation is viable for inverter-interfaced microgrids**
- **A downside is that pilot relaying is likely required given short line lengths & change in system configuration from switching – operating area will be large compared to the line impedance**
- **If a communications channel is required, there are more sophisticated methods such as state-estimation based protection that can operate with the failure of one or more sensors**

Exceptional service in the national interest

Sandia National Laboratories






Distribution Voltage Regulation using DER Grid-Support Functions

New Mexico Established Program to Stimulate Competitive Research (NM EPSCoR) Webinar
22 Nov, 2019

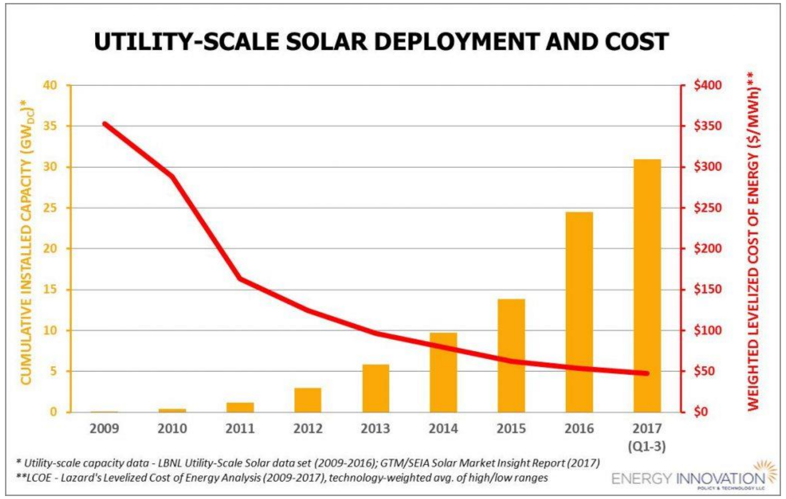
Jay Johnson
Renewable and Distributed Systems Integration
Sandia National Laboratories

CONNECTED ENERGY
Georgia Institute of Technology
nationalgrid
SUNSPEC ALLIANCE
PNM
EPRI ELECTRIC POWER RESEARCH INSTITUTE
SUNPOWER

SAND2019-14165 PE

Background

- Context
  - Total installed capacity of PV is growing fast
  - Large growth expected in distribution systems
- Problem
  - Grid is slow to evolve, we encounter technical challenges with voltage/frequency regulation, protection, etc.
  - Unless mitigated, these challenges will make it increasingly difficult and costly to continue integrating renewable energy
- Solution: advanced inverters
  - Actively support voltage and frequency by modulating output
  - Have high tolerance to grid disturbances
  - Interact with the system via communications
- Research questions
  - What is the best technique for providing voltage regulation?
  - How can the methods be evaluated with physical devices prior to field implementation?



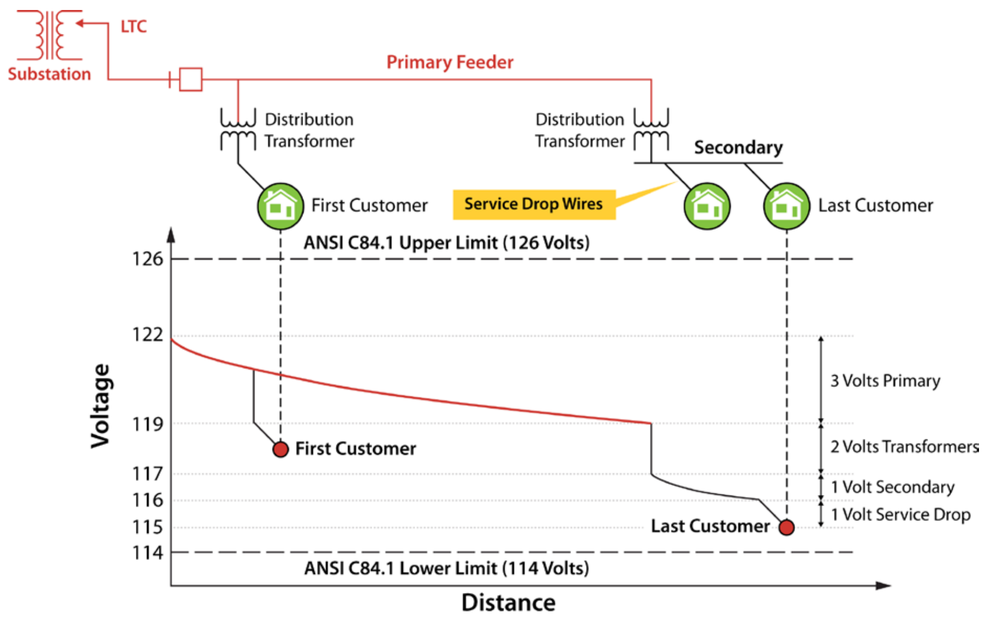
...Faster than a tap changer

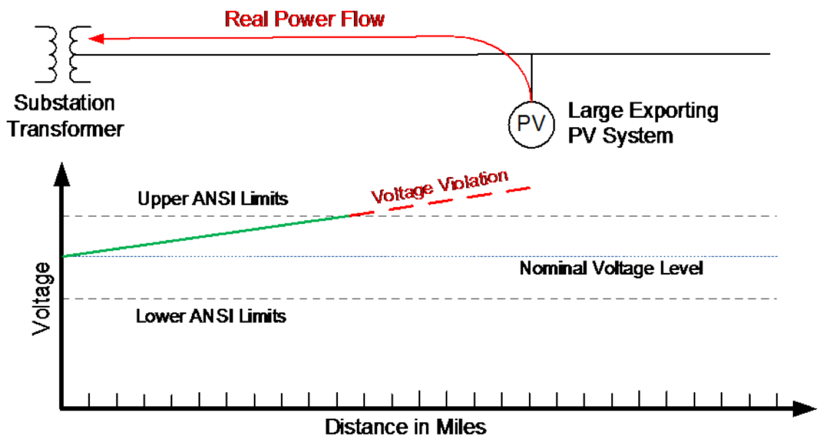
...More powerful than a rotating machine

...Able to leap deep voltage sags in a single bound

Courtessy of B. Lydic, Fronius

Distribution Voltage Regulation





Voltage regulation on a feeder without distributed generation.

Voltage regulation on a feeder with distributed generation.

Solution: Use DER grid-support functions with reactive power capabilities.

- **Cost-effective: no additional equipment required**
- **Logical: employs devices which are causing voltage rise to mitigate the problem**

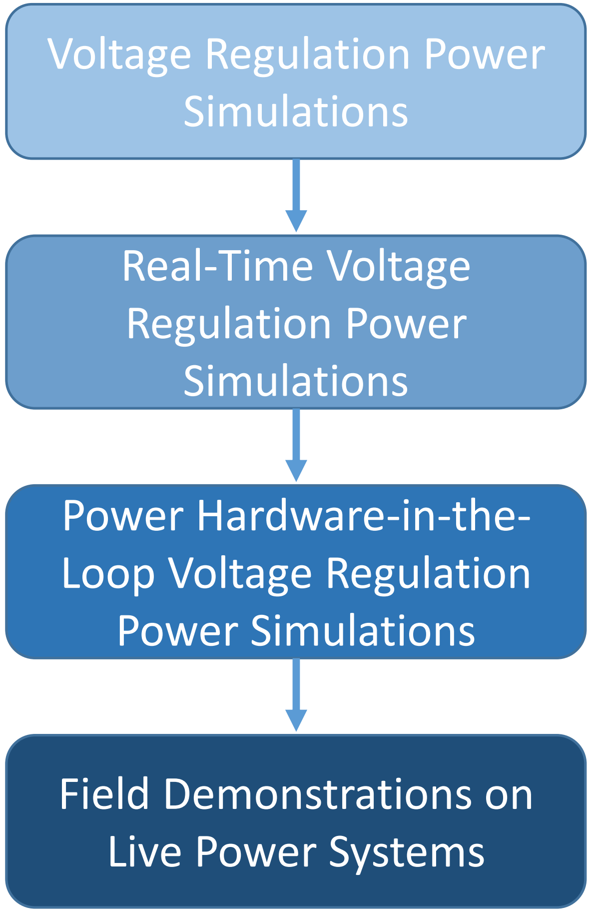
Images: B. Palmintier et al., On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System, NREL/TP-5D00-65331, May 2016.

ENERGISE ProDROMOS Project

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

The project created an Advanced Distribution Management System (ADMS) that captures distribution circuit telemetry, performed state estimation, and issued optimal DER setpoints based on PV production forecasts.

Team used PHIL experiments to gain confidence in control algorithms, verify communication interfaces, and predict performance prior to deploying the ADMS on a live feeder in Massachusetts.



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

Options for Voltage Regulation using Grid-Support Functions

Distributed Autonomous Control

- Function: volt-var or volt-watt
- Pros: simple, requires little or no communications, DER locations not needed
- Cons: does not reach global optimum

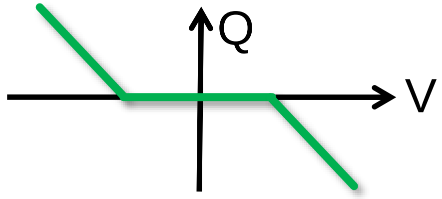
Extremum Seeking Control (ESC)

- Function: power factor or a new grid-support function
- Pros: can achieve global optimum
- Cons: requires fitness function broadcast or PF calculation by central entity

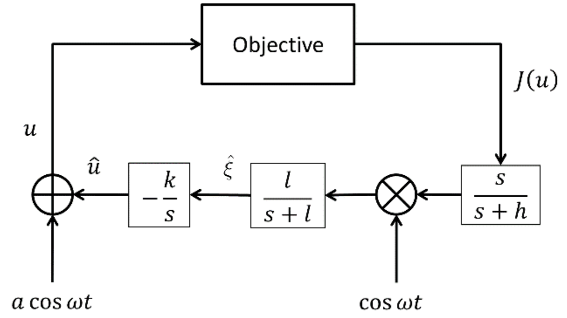
Optimal Power Factor Control

- 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

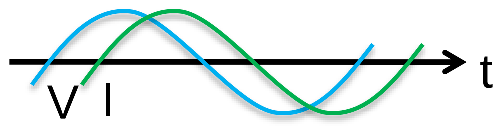
Volt-Var Mode



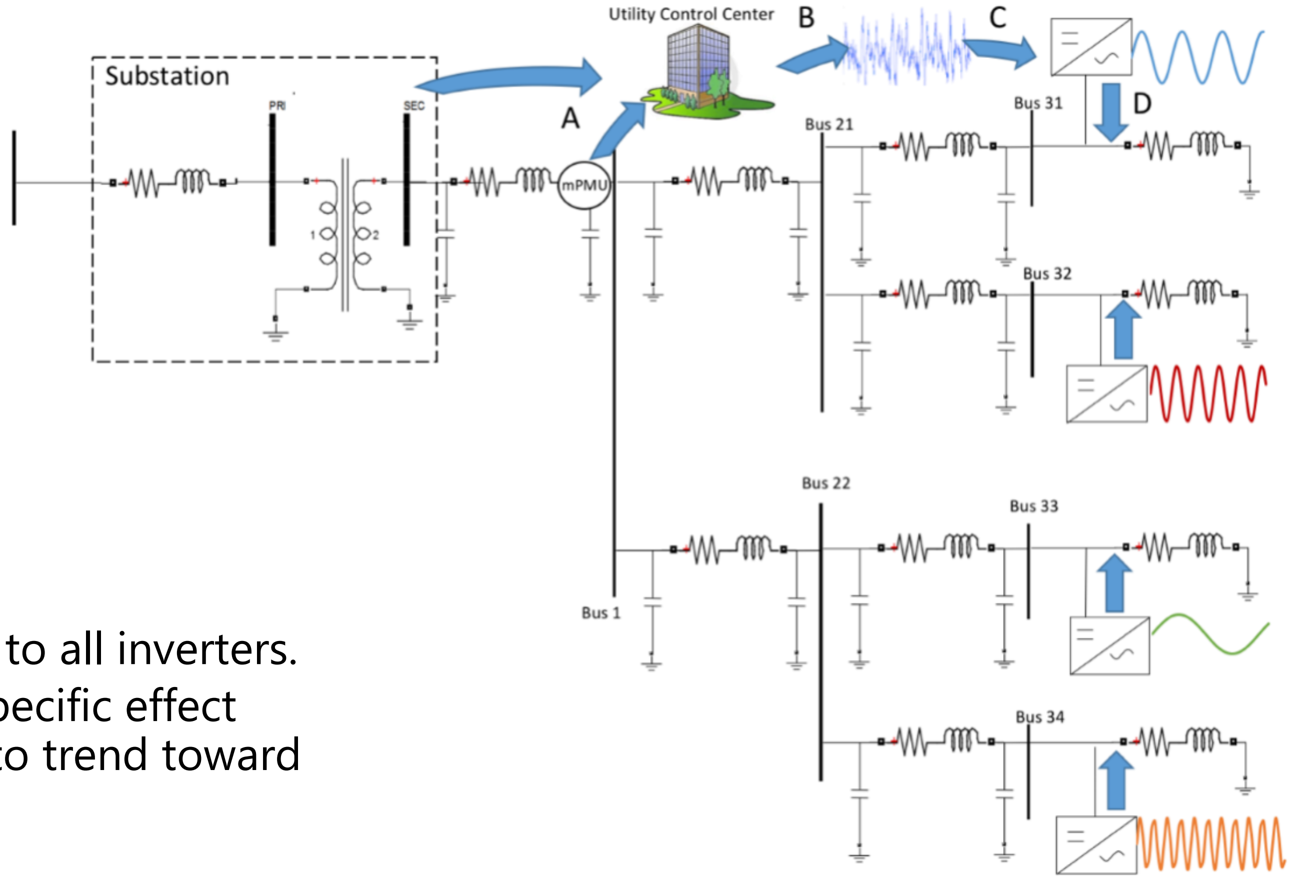
ESC



Optimal Power Factor



Extremum Seeking Control



Extremum Seeking Control (ESC) was 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

Particle Swarm Optimization (PSO) Optimal Power Flow (OPF)

In the PSO OPF method, time-series **OpenDSS** simulations were wrapped in an optimization to calculate the PF values for each PV inverter.

- RT power data for each of the buses and the PV forecasts were used to generate a time-series simulation by setting the active and reactive power levels of dynamic loads in the OpenDSS model.
- The OpenDSS load data was populated by Georgia Tech's Integrated Grounding System Analysis program for Windows (WinIGS) state estimation solution.
  - Active and reactive loads were assumed static.
- Future PV production estimations were populated by PV persistence forecasts.

Objective Function:

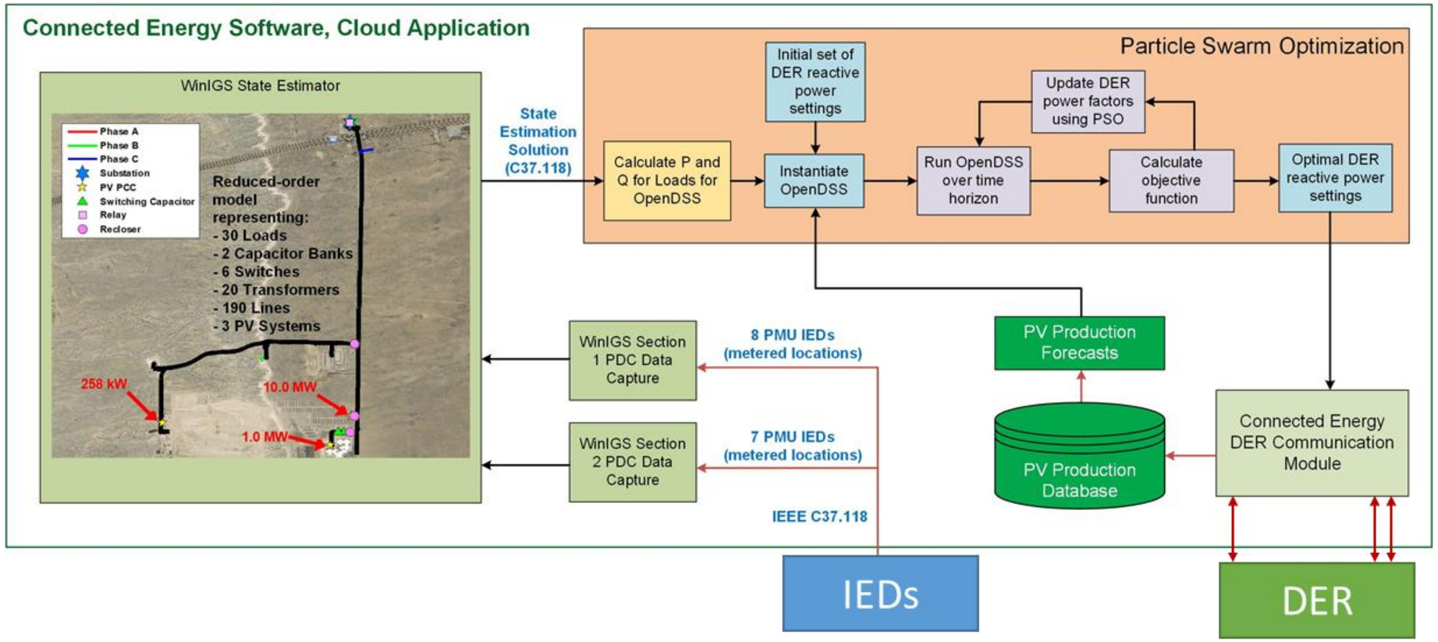
$$\min_{PF} w_0 \delta_{violation}(V) + w_1 \sigma(V - V_{base}) + w_2 C(PF)$$

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

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

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

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



Particle Swarm Optimization Block Diagram.

Creating Realistic Power Simulations

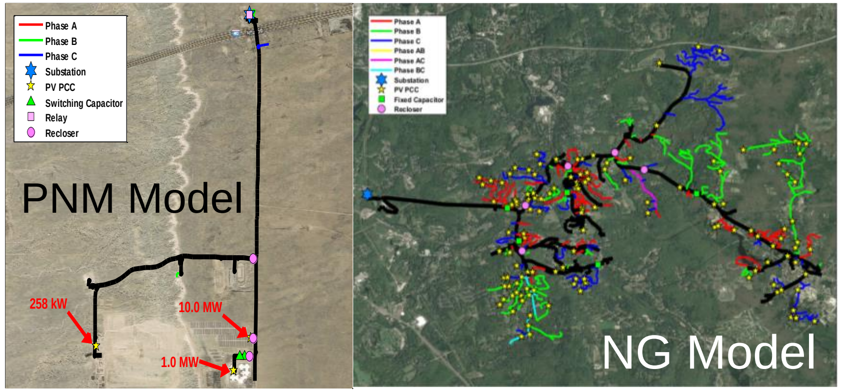
- Feeder models, based on existing distribution systems were reduced to smaller equivalent distribution systems using the **OpenDSS.**
- These models were migrated into **MATLAB/Simulink** and simulated in RT with a simulated PV inverter.
- The **OPAL-RT** platform was used to demonstrate the capabilities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

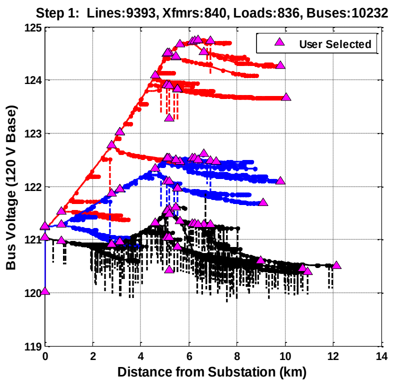
Collect information on distribution system. → Reduce model and simulate distribution system in **OpenDSS**. → Create **RT** simulation in **MATLAB/Simulink** on the **OPAL-RT**. → Obtain **RT-PHIL** experimental results in **MATLAB/Simulink** on the **OPAL-RT**.

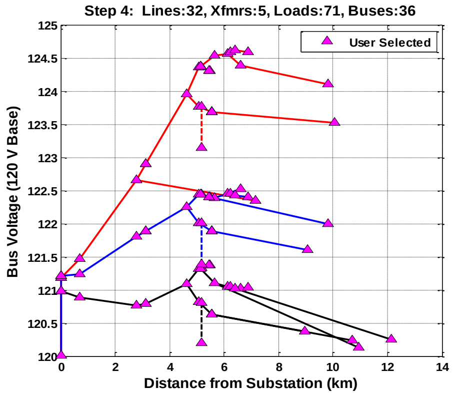
Before Reduction			
Line	Xfmr	Load	Bus
9393	840	836	10232

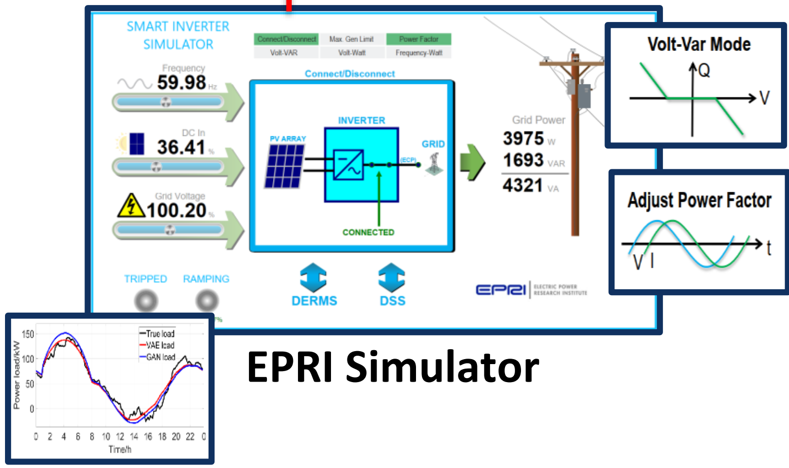
After Reduction			
Line	Xfmr	Load	Bus
32	5	71	36

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





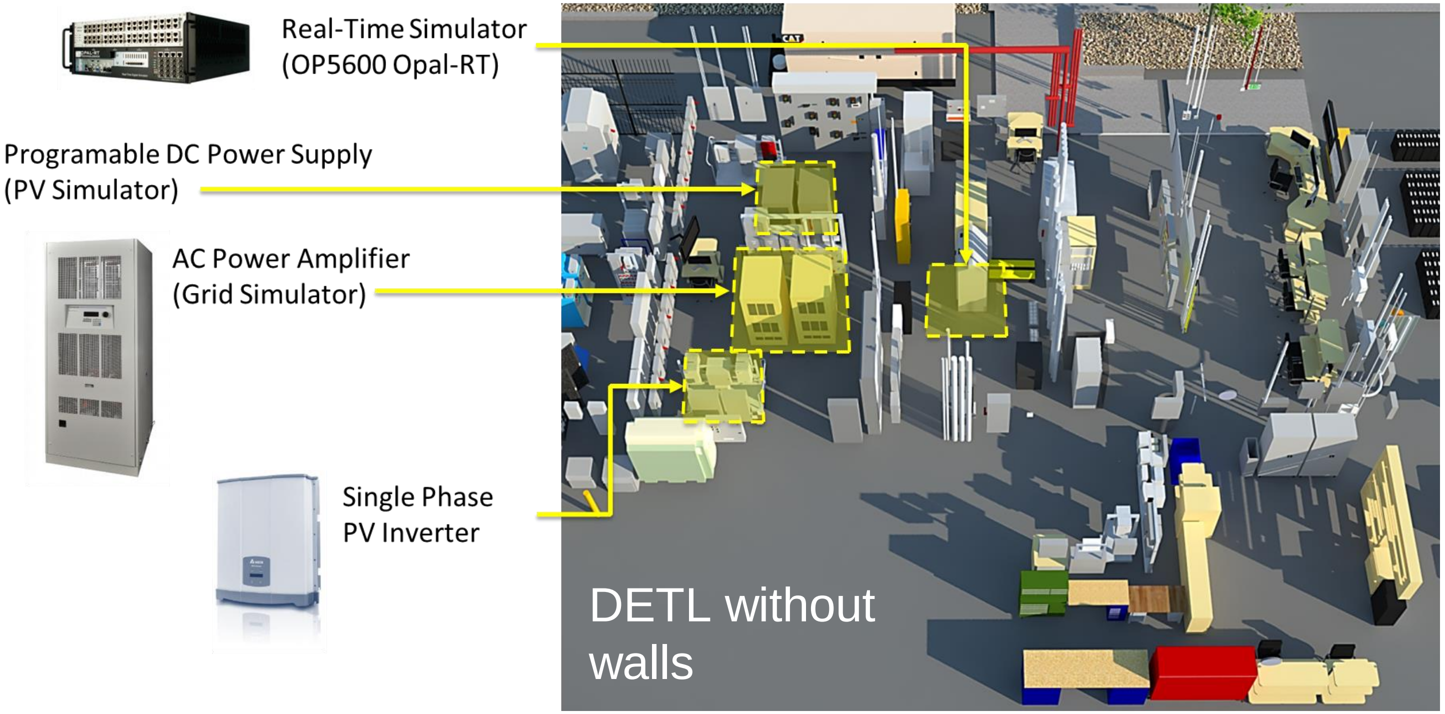




EPRI Simulator

Distributed Energy Technology Laboratory at SNL

- The **Distributed Energy Technologies Laboratory (DETL)**, located at Sandia National Laboratories in Albuquerque, NM, provides power systems and power electronics testing capabilities.
- DETL includes a 480 V, 3-phase microgrid, with interconnections to the utility grid and several DER devices (PV inverters, microturbines, fuel cells, reciprocating engine-generators, and energy storage systems).
- The laboratory also has an OPAL-RT real-time simulator used to perform RT-PHIL tests with 1ϕ or 3ϕ PV inverters, a 100 microinverter testbed, and other DER.
- DETL researchers have extensive expertise in **DER grid-integration**.



PSO OPF Real-Time Power Hardware-in-the-Loop Setup

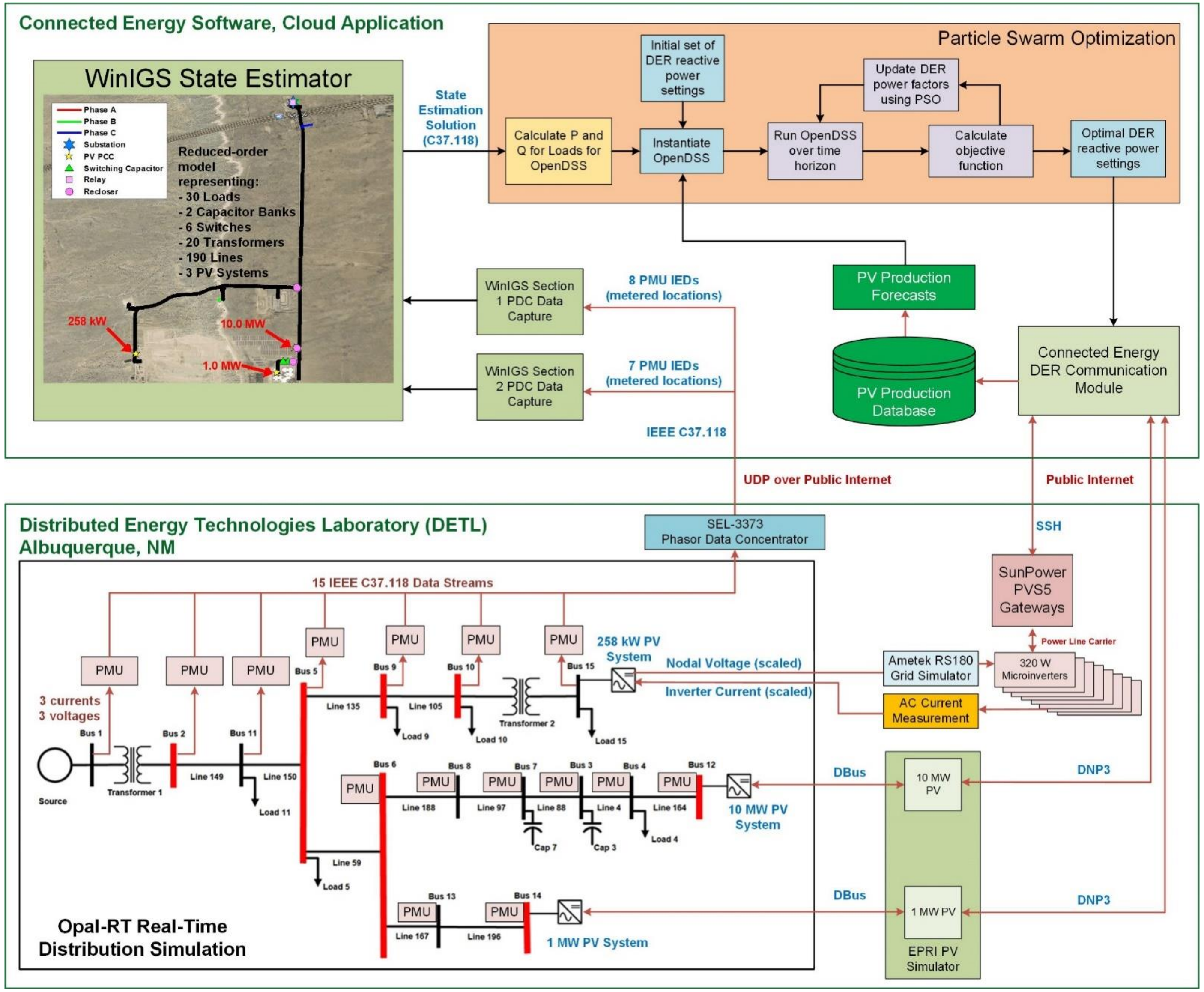
OPAL-RT Communication Interfaces

- PMU C37.118 to state estimator
- OPAL-RT DataBus Interface receives P/Q values for EPRI DER 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 were issued through Modbus and IEEE 1815 (DNP3) commands.

RT-PHIL allows for an **affordable and repeatable alternative** to testing physical devices under real operating conditions before they are connected to an actual system.



PNM RT Simulation Results

There is only a small improvement in bus voltage when implementing Volt-Var with a relatively passive curve.

ESC and PSO improve voltage regulation at the PCC of PV inverter 2 and globally.

- The average bus voltage is close to nominal (good)
- The maximum voltage is reduced substantially (good)
- The minimum voltage is reduced (bad)

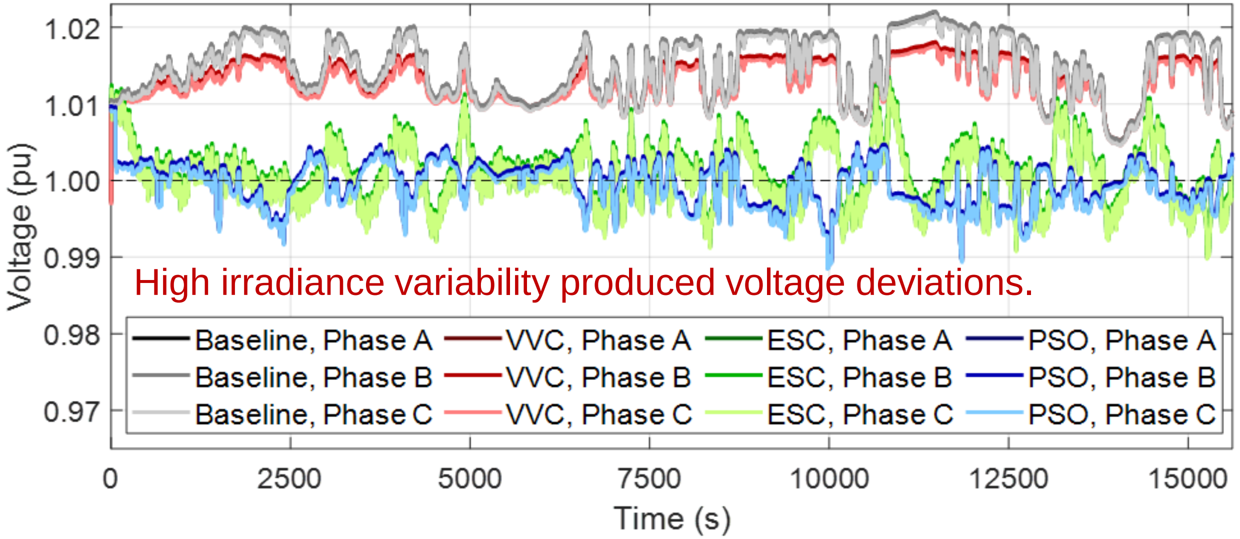
$$score = \frac{1}{T}\int_{t=0}^{t_{end}} \sum_{n=1}^{N} \left(|v_{bl,n} - v_{nom,n}| - |v_{reg,n} - v_{nom,n}|\right) dt$$

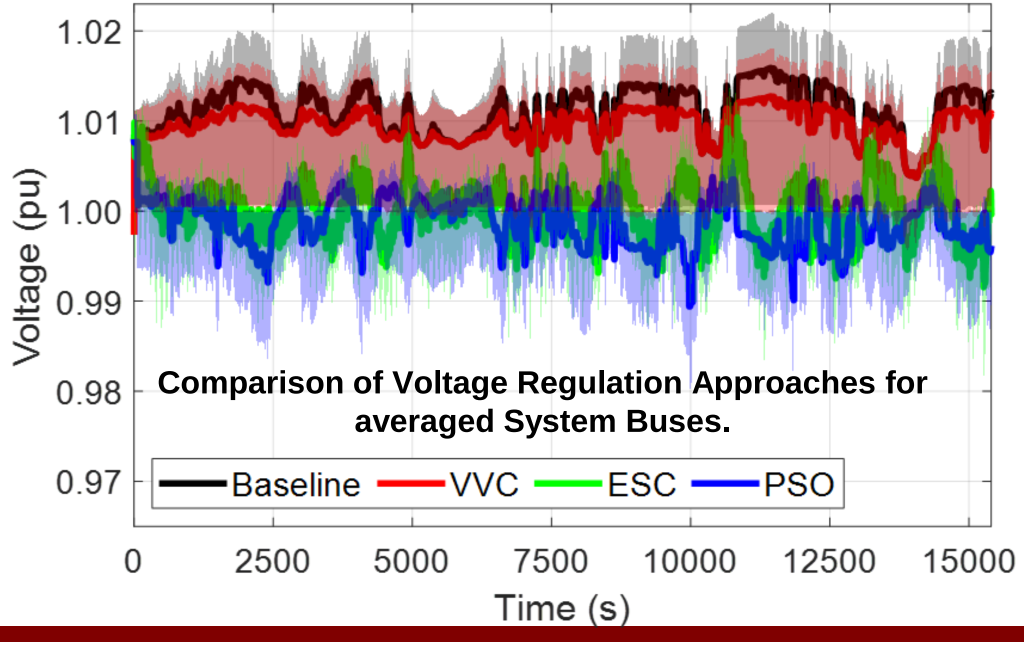
where:

v_{bl}	Baseline Voltage
v_{nom}	Target Voltage
v_{reg}	Voltage with control applied
T	Time Period
n	bus
t	time

PNM 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**	

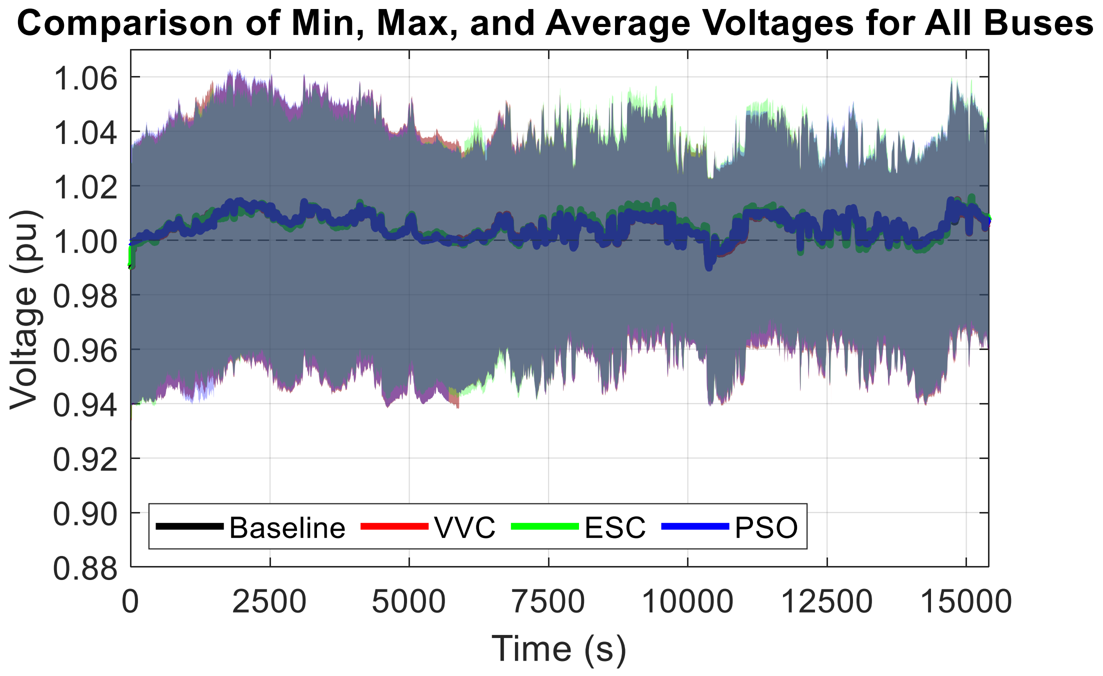
Voltage at PV inverter 2 PCC.



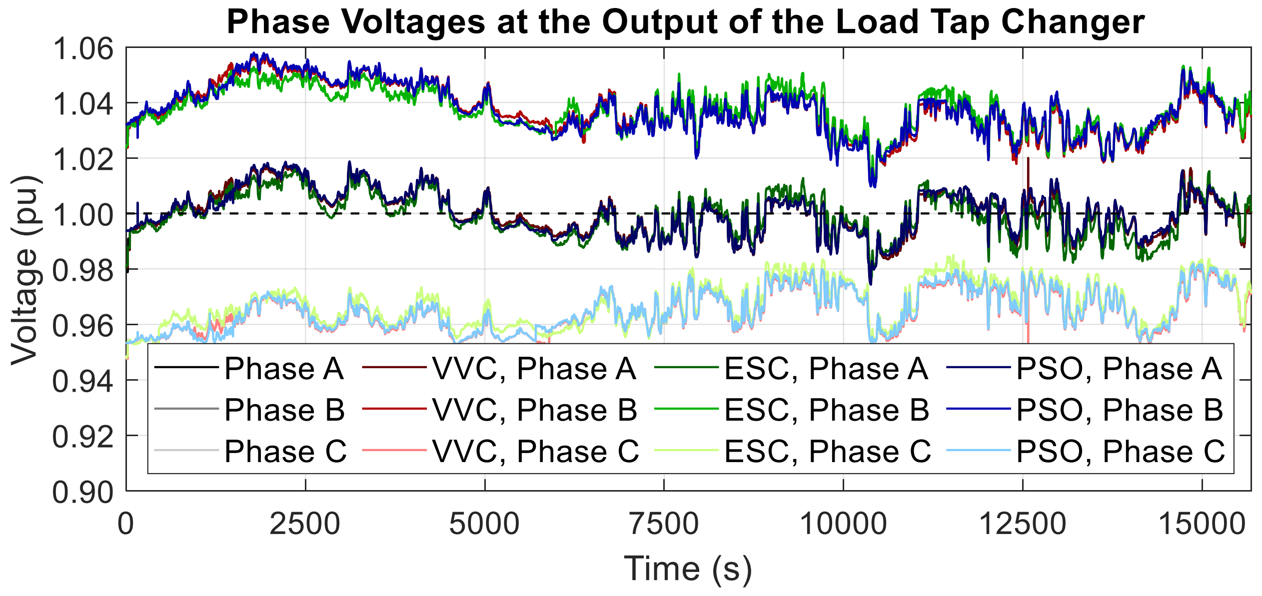


NG Simulations with 3ϕ inverters at Old Upton Road

- The National Grid system was highly unbalanced.
- None of the voltage regulation techniques were capable of correcting the voltage deviations using the 3ϕ inverters at Old Upton Rd.



Comparison of Voltage Regulation Approaches for averaged System Buses.



Voltage at PV inverter 1 PCC.

- Question: if all the PV systems on this feeder were used for voltage regulation (not just Old Upton Rd) would there be a big improvement?

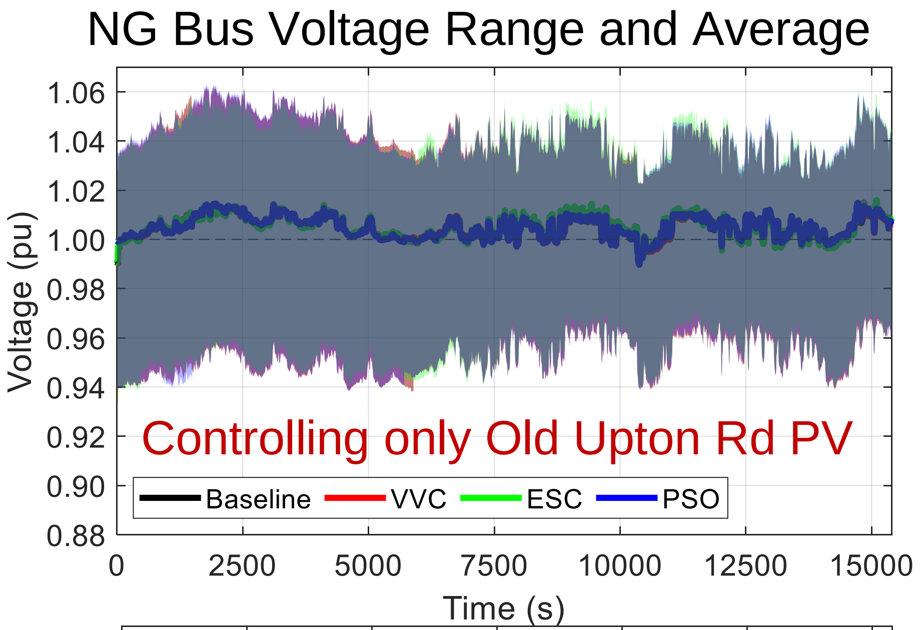
NG Simulations with All Inverters

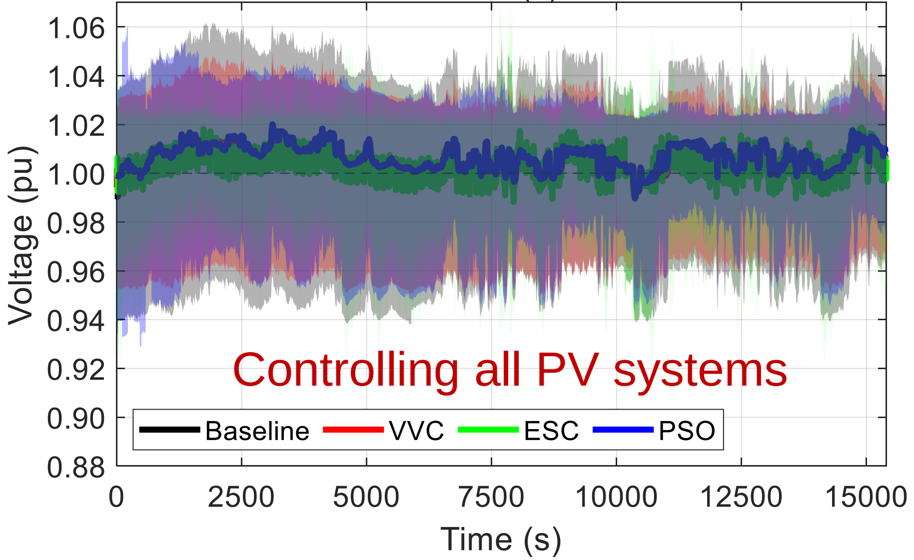
- PV size, location, and rating of the PV inverters are important for the control.
- Controlling all PV generated larger excursions, but in general kept the voltages closer to nominal.
  - The improvement is clear in the feeder scoring results.

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

NG Feeder Score Controlling a Single PV Site					
	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**	

NG Feeder Score Controlling All PV System (including 1ϕ devices)					
	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**	

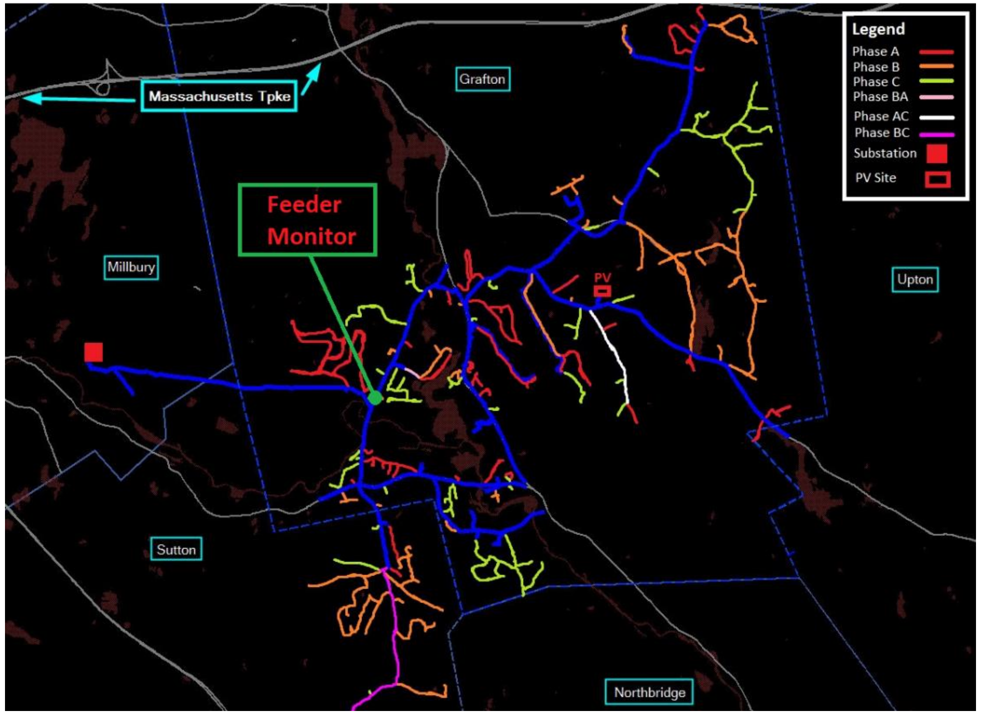




National Grid PV System

The team ran Volt-Var, ESC, and PSO OPF control techniques on the live National Grid feeder in Grafton, MA.

- 28 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



684 kW_{dc}/672 kW_{ac} Old Upton Rd PV Installation

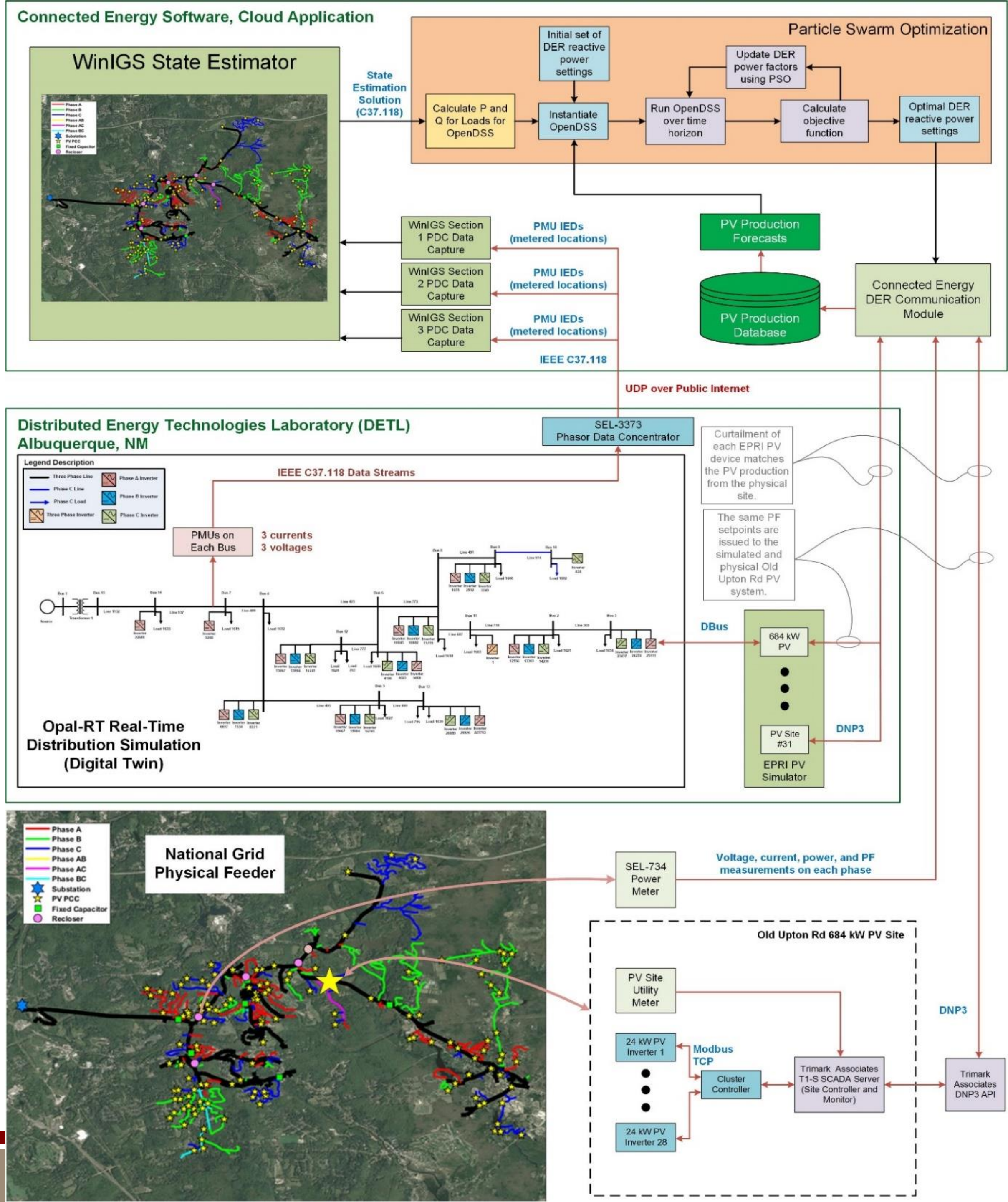
Digital Twin Concept for PSO

Problem

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

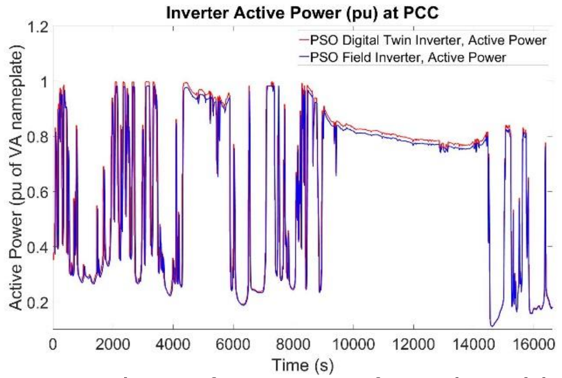
Implementation

- 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 power was mapped from physical system to simulated DER device using the curtailment function
- PV PF setpoints are sent to the physical and virtual PV system
- This does not account for the current load (only pre-recorded versions)

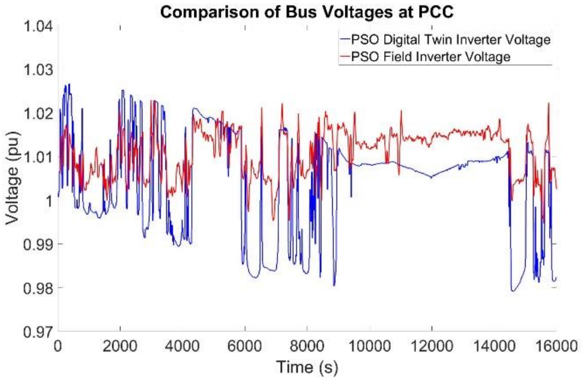


PSO on NG Feeder

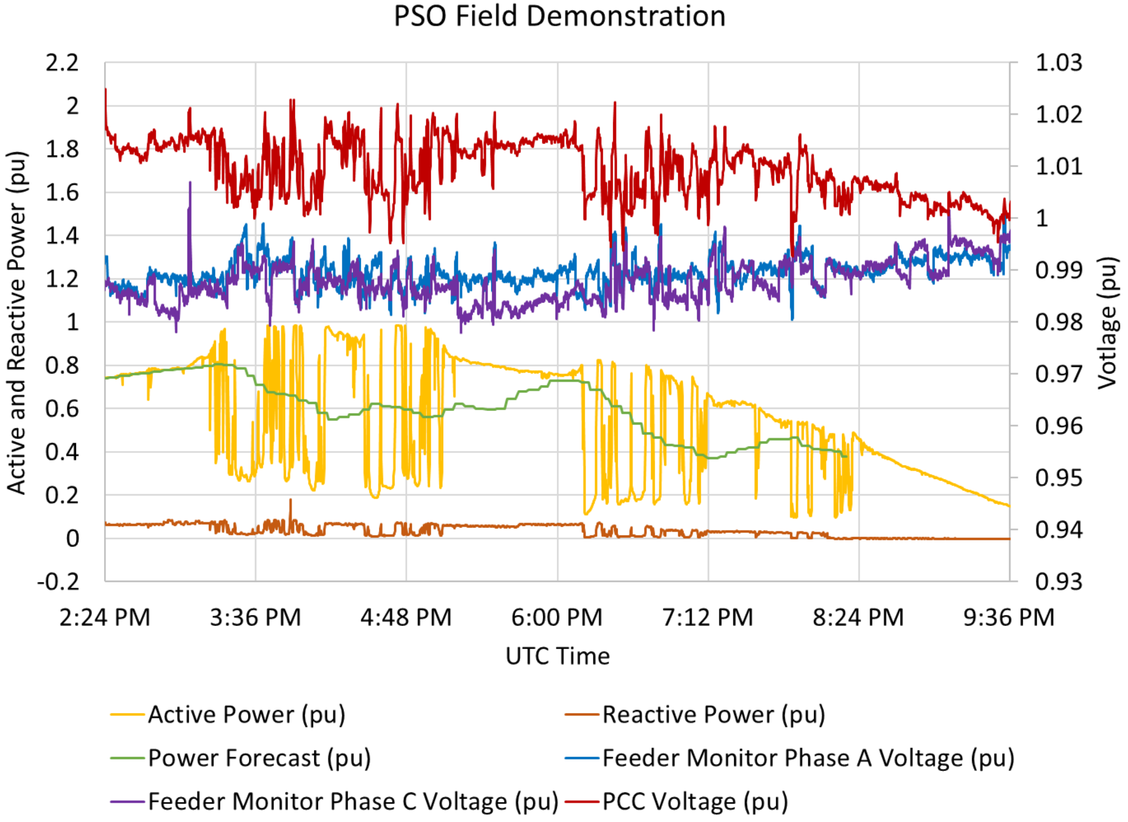
- Forecast matched PV production
- Line drop compensation should be disabled so that voltage regulation is completed with a single controller
- PSO operated near unity and could do little to help the voltage imbalance of the feeder—just like the other methods.
- Since Old Upton Rd only included three-phase inverters it was not possible to help the phase imbalance but did attempt to move the feeder voltages toward nominal.
- Digital twin method appears to work well!



Comparison of PV power from the Old Upton Rd site and the digital twin represented by the curtailed EPRI DER simulator.



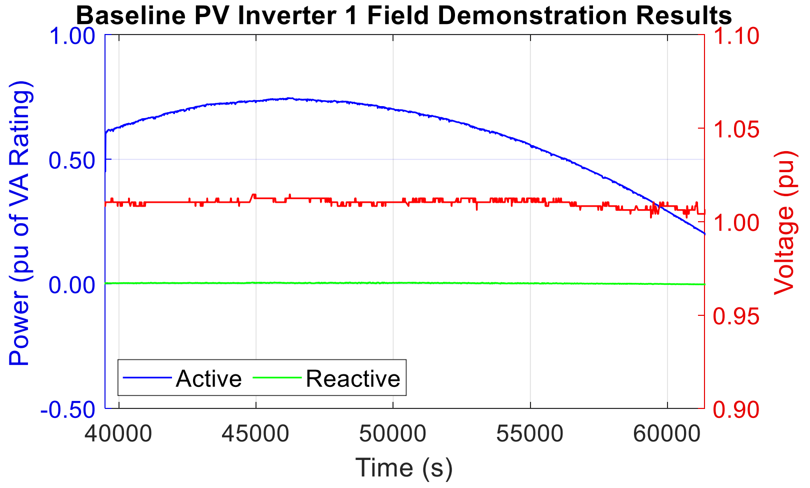
PCC RT-Lab and PCC Field Voltage Comparison.

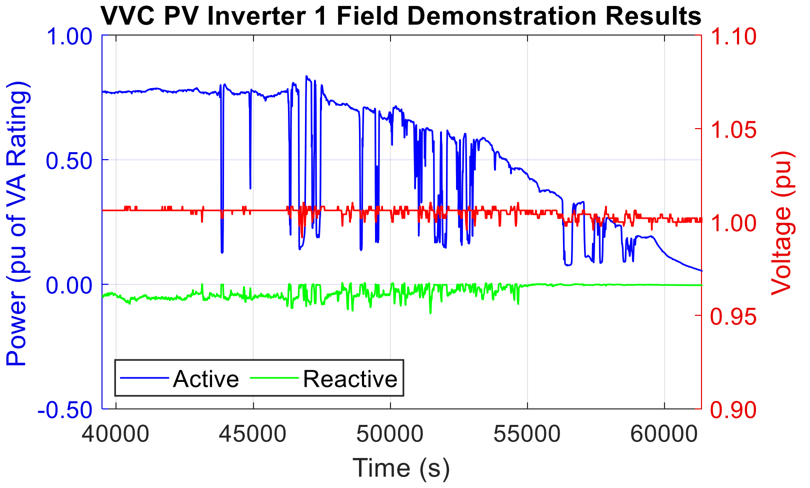


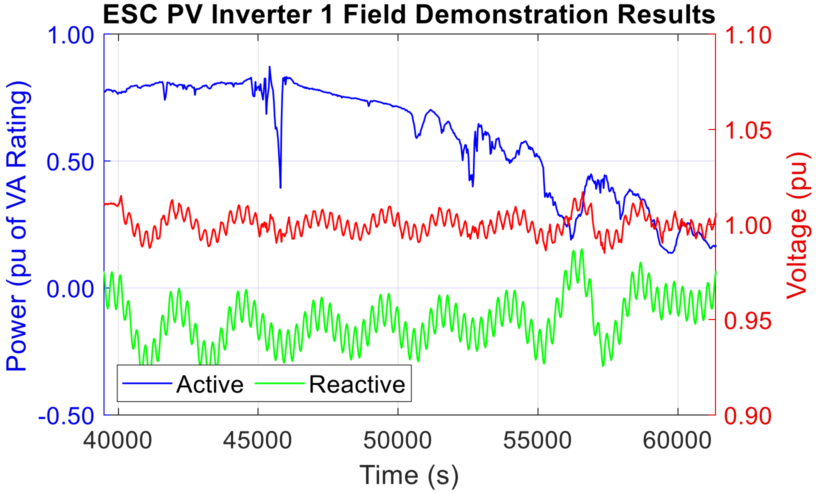
When PV output is high, there is low voltage because there is a voltage regulator with line drop compensation on this feeder.

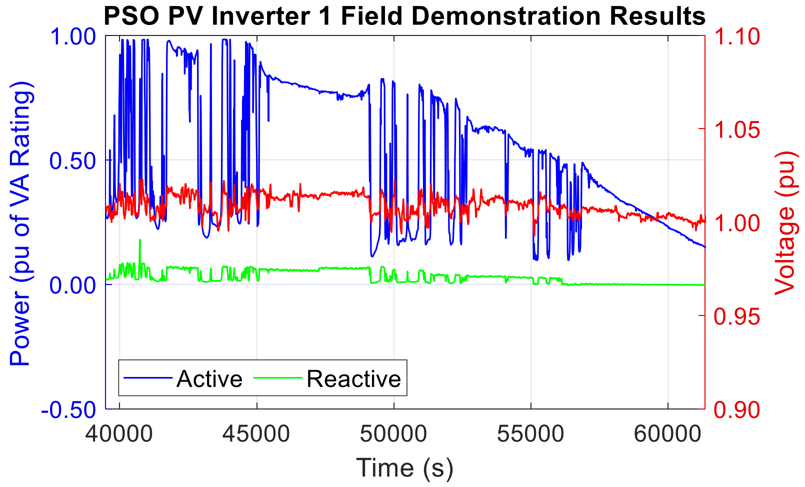
NG Field Demonstration

- All the voltage regulation methods were deployed on the live feeder by programming the volt-var or power factor setpoints in the 28 PV inverters at Old Upton Rd.
- Difficult (impossible?) to compare voltage regulation methods in the field because of different irradiance profiles and voltage regulation equipment on the feeder.
- Average PCC voltage close to nominal for all methods.









Project Conclusions and Accomplishments

- **Demonstrated incremental development approach was effective** (simulation to real time to PHIL to field)
  - Communications between measurement equipment, ADMS controllers, and DER devices was verified.
  - Built 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.
  - None of the methods were capable of solving the phase imbalance issue with three-phase inverters.
- **Open question and observations**:
  - How well could negative and zero sequence current from 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.

ProDROMOS GitHub Repository: https://github.com/sunspec/prodromos/

Thank You

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