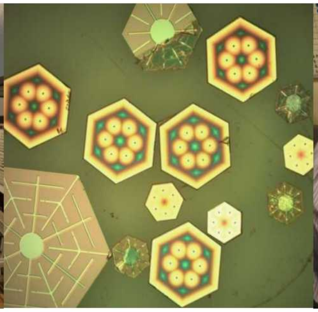
SAND2018-6142C

# Distribution Voltage Regulation using Extremum Seeking Control with Power Hardware-in-the-Loop

**Jay Johnson,[1] Adam Summers,[1,2] Rachid Darbali,[3] Javier Hernandez-Alvidrez,[4] Jimmy Quiroz,[1] Dan Arnold,[5] and Jithendar Anandan[6]**

[1]Sandia National Laboratories, Albuquerque, NM
[2]University of New Mexico, Albuquerque, NM
[3]University of Puerto Rico at Mayagüez, Mayagüez, PR
[4]New Mexico State University, Las Cruces, NM
[5]Lawrence Berkeley National Laboratory, Berkeley, CA
[6]Electric Power Research Institute, Knoxville, TN

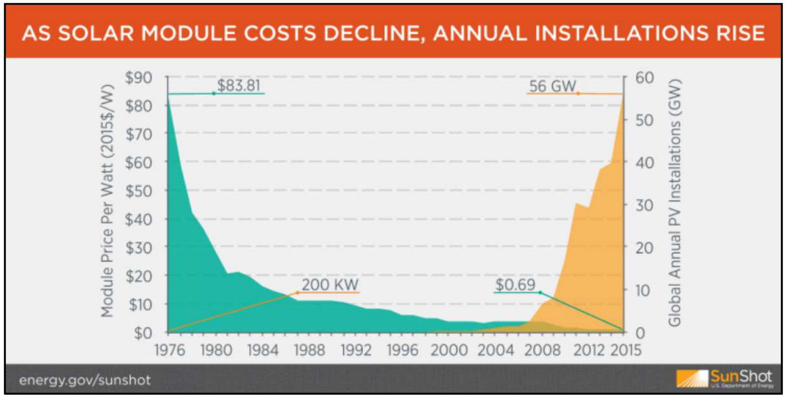




**World Conference on Photovoltaic Energy Conversion (WCPEC-7)**
June 10-15, 2018
Waikoloa, Hawaii

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

# 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





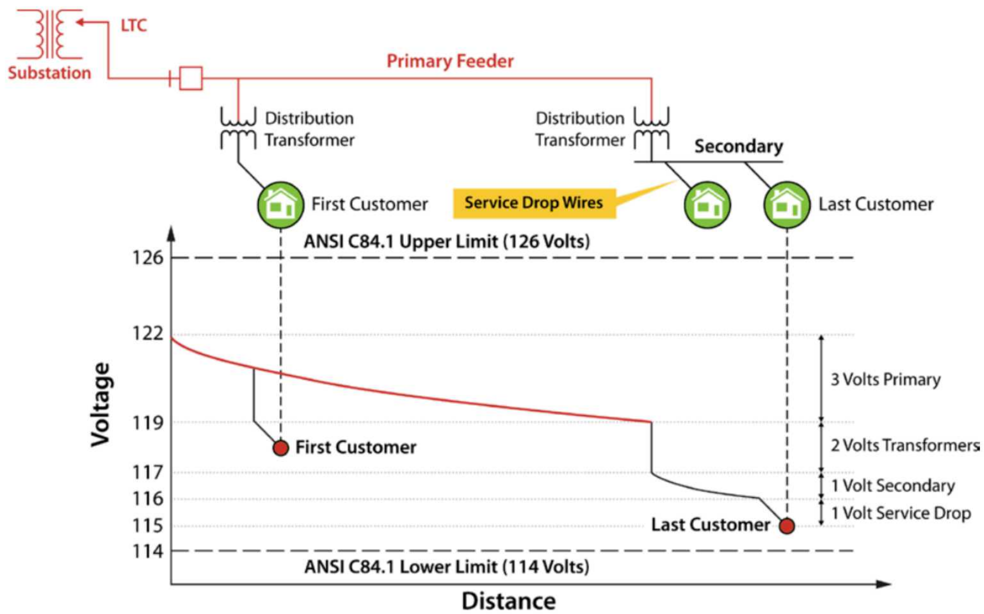
***...Faster than a tap changer***

***...More powerful than a rotating machine***

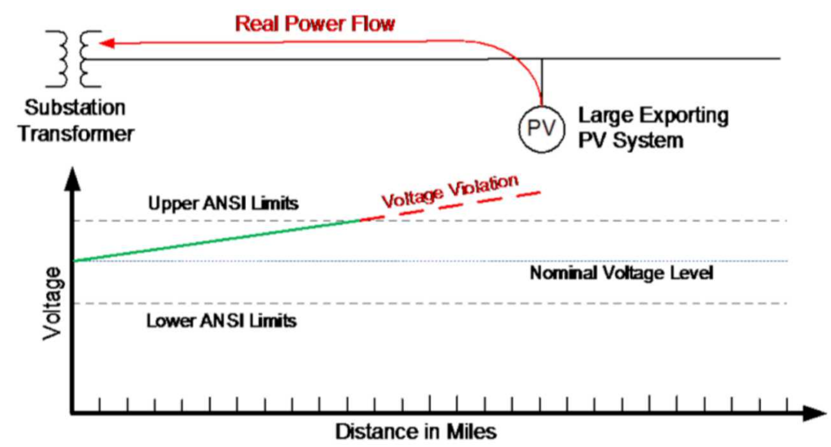
***...Able to leap deep voltage sags in a single bound***

Courtessy of B. Lydic, Fronius

# Distribution Voltage Regulation




**Voltage regulation on a feeder without distributed generation.**




**Voltage regulation on a feeder with distributed generation.**

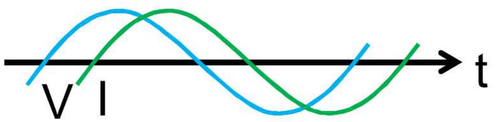
**Solution: Use DER grid-support functions with reactive power capabilities.**
- **Cost-effective: no additional equipment required**
- **Logical: employs devices which are causing voltage rise to mitigate the problem**

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.

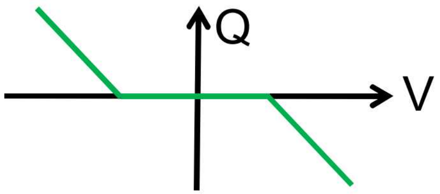
# Options for Voltage Regulation using Grid-Support Functions

- **Centralized 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
- **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: new grid-support function
  - Pros: can achieve global optimum
  - Cons: requires fitness function broadcast, ideally new inverter functionality

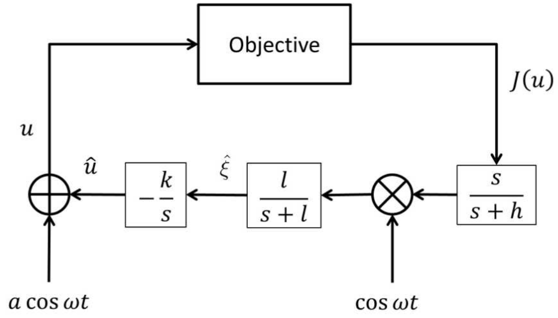
**Adjust Power Factor**



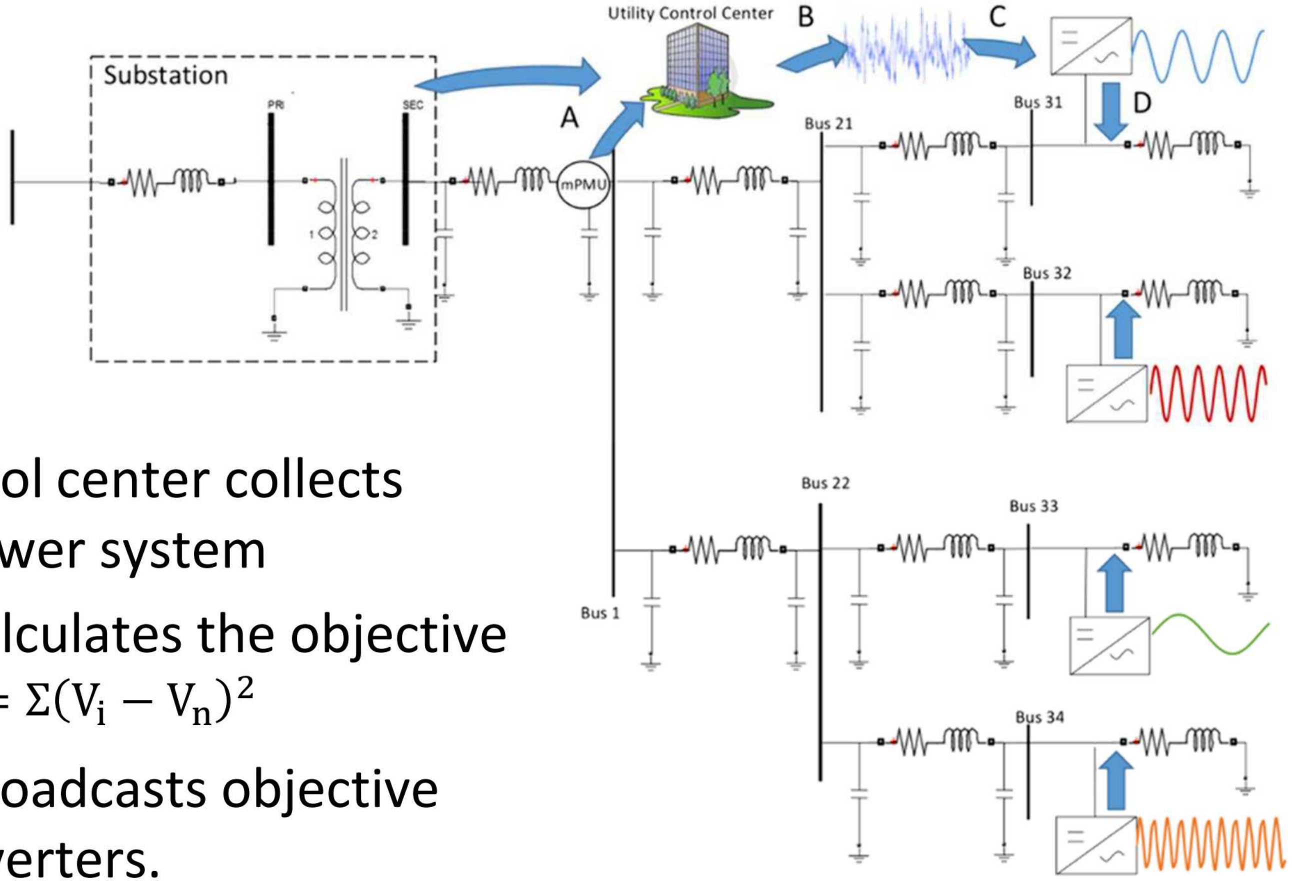

**Volt-Var Mode**




**ESC**



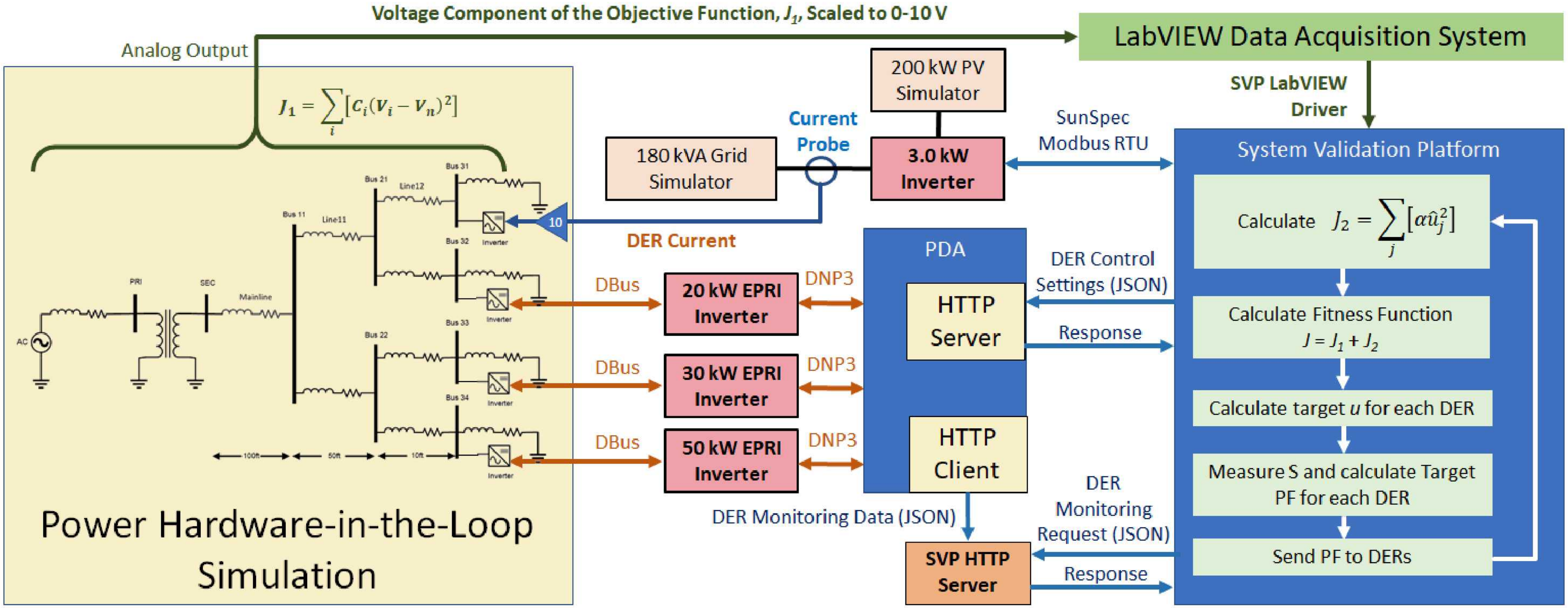
# Extremum Seeking Control Steps




A. Centralized control center collects data from the power system
B. Control center calculates the objective function, e.g., $J = \Sigma(\mathrm{V_i} - \mathrm{V_n})^2$
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.

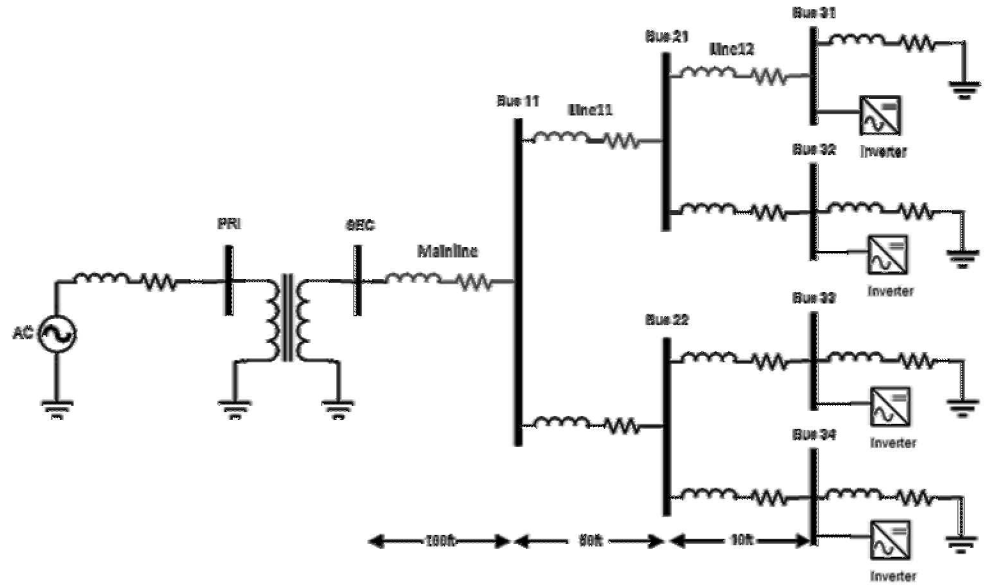
# Implementation with PHIL System

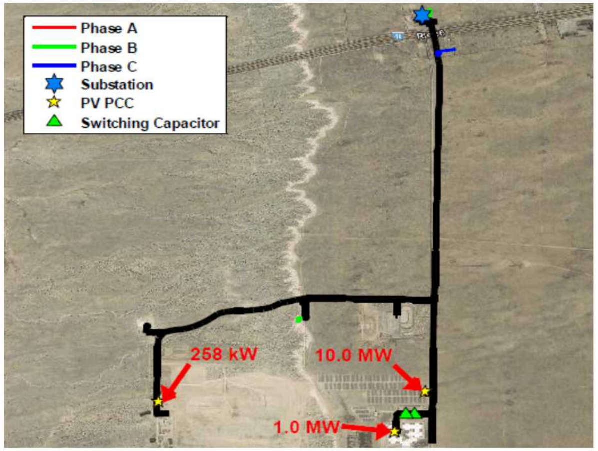
- Opal-RT power hardware-in-the-loop (PHIL) experiments conducted to demonstrate the technology on larger distribution circuits.

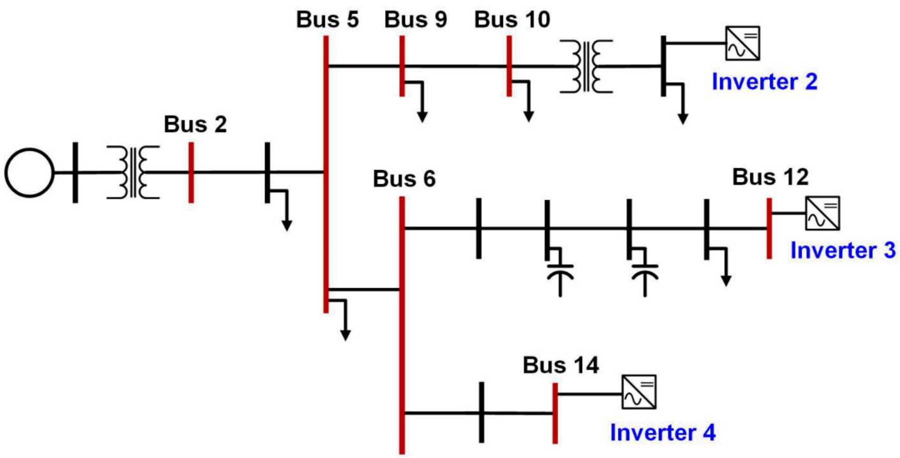


# Implementation with PHIL System

- Two feeders used for this study.
  - 7-bus neighborhood model
  - PNM rural feeder west of Albuquerque with ~440% PV penetration.

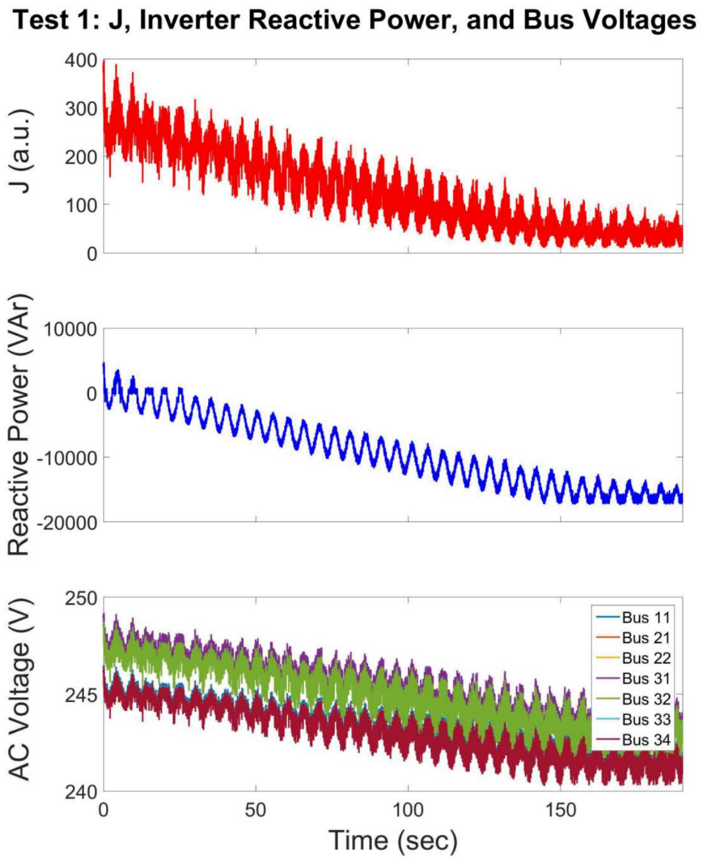


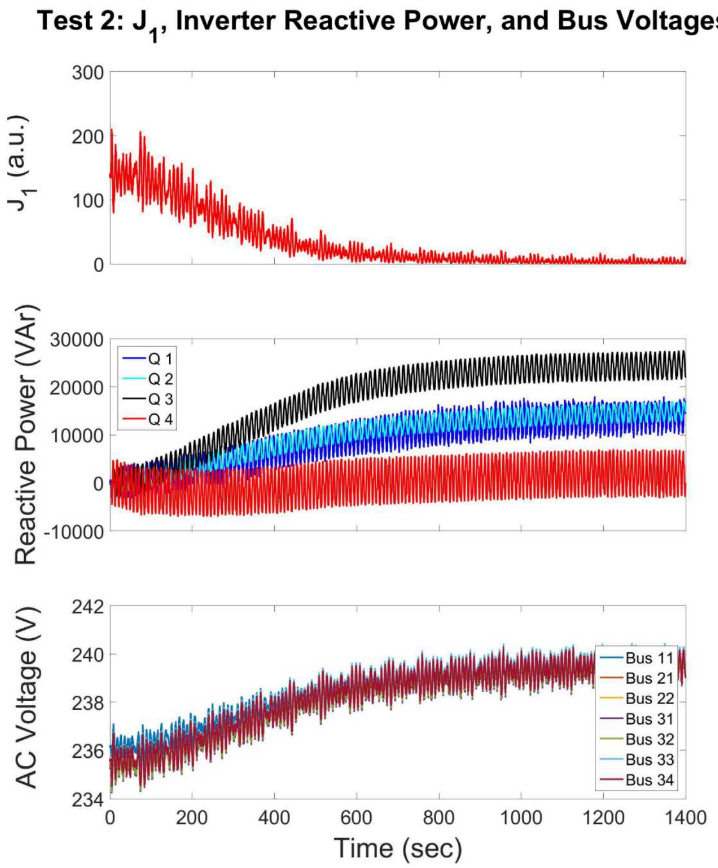



# Results

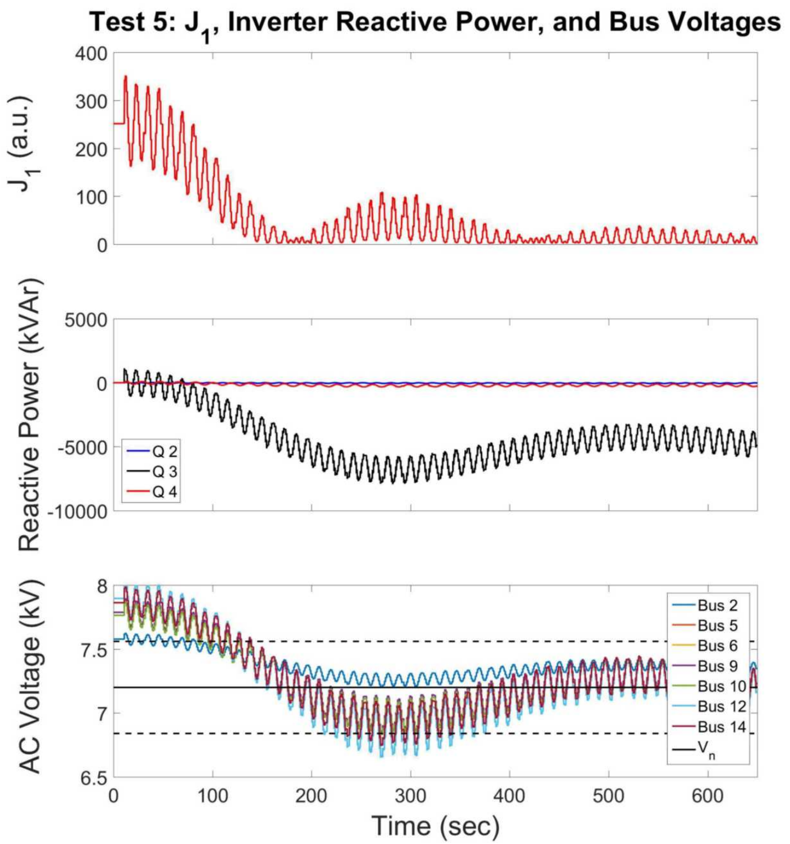
- ESC adjusts reactive power to reduce the overvoltage conditions on the simulated power system buses.



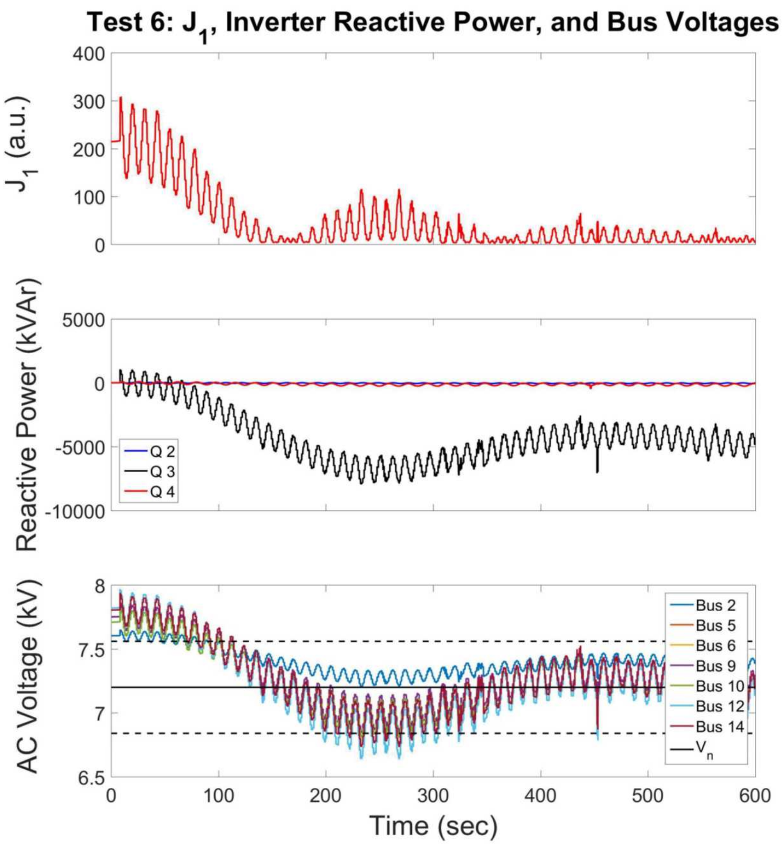



# Results with Variable Irradiance

- The 3 inverters have PV range of ±0.2 so they can produce a large range of reactive power, even at low irradiance.



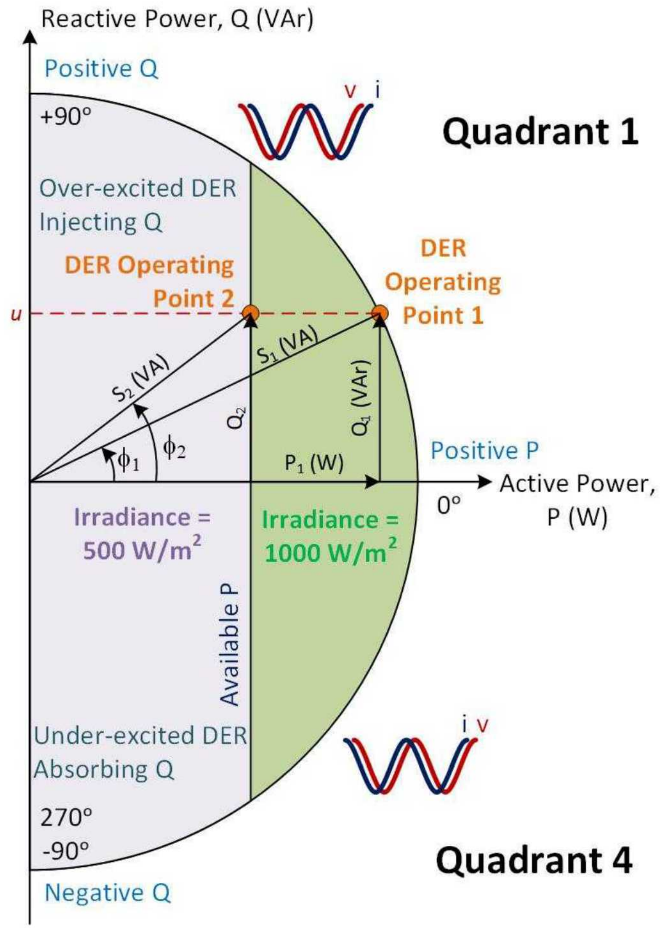

(C) Extremum Seeking Control on the PNM Feeder with 1000 W/m$^2$ Irradiance.

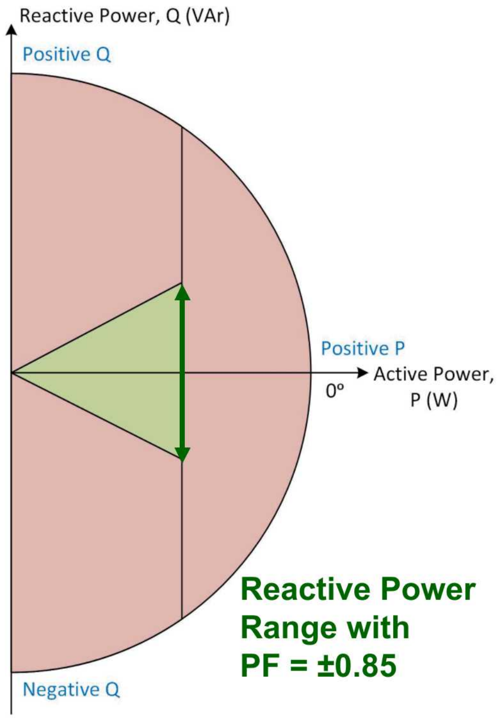


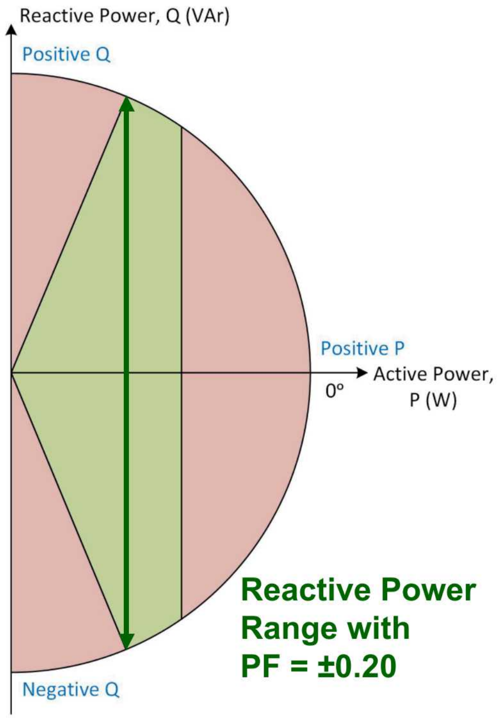

(D) Extremum Seeking Control on the PNM Feeder with Variable Irradiance.

# ESC Considerations with Variable Irradiance

- Reactive power considerations with variable irradiance



# Conclusion

- Extremum seeking control can be used for a range of power system objectives when speed is not critical and an objective function can be broadcast to control equipment. Some applications are:
  - Voltage regulation[1]
  - Transmission services[2]
  - Microgrid control

- Future work:
  - 1+ day long ESC simulations with solar variability
  - Tune control parameters and increase ESC response time
  - Run experiments with additional distribution circuit models

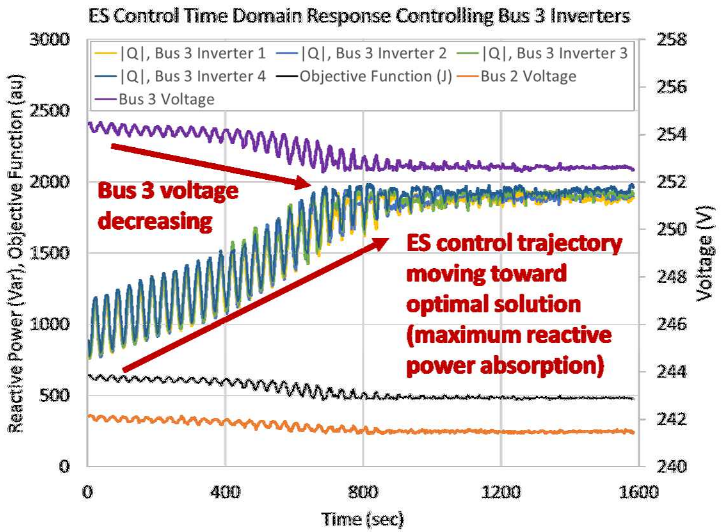

1. D.B. Arnold, et al., Model-Free Optimal Control of VAR Resources in Distribution Systems: An Extremum Seeking Approach, IEEE Trans. Power Systems, Vol. 31. No. 5, Sept. 2016.
2. D. B. Arnold, M. D. Sankur, M. Negrete-Pincetic and D. Callaway, "Model-Free Optimal Coordination of Distributed Energy Resources for Provisioning Transmission-Level Services," in IEEE Transactions on Power Systems, vol. PP, no. 99, pp. 1-1, 2017.

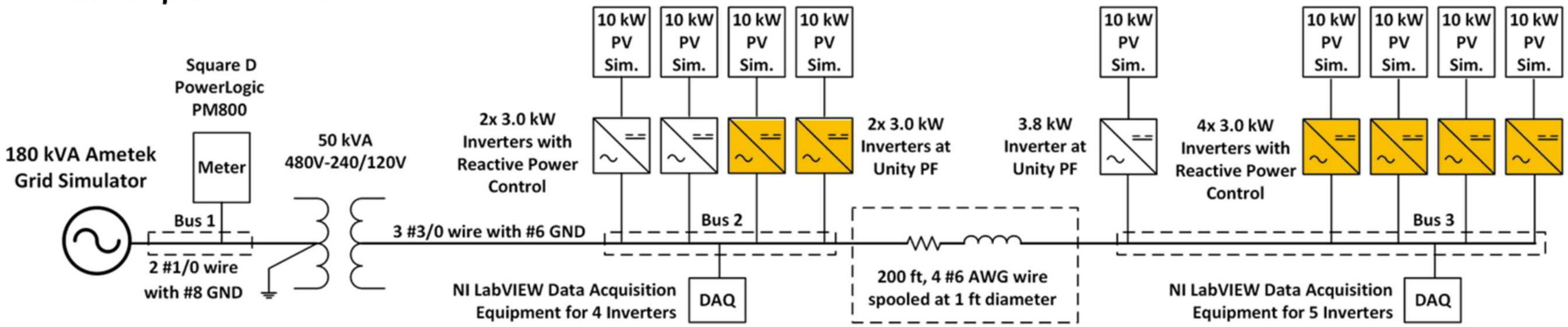
# Thank You!

**Jay Johnson**
Renewable and Distributed Systems Integration
Sandia National Laboratories
P.O. Box 5800 MS1033
Albuquerque, NM 87185-1033
Phone: 505-284-9586
jjohns2@sandia.gov

# Prior Experimental Work

- Fixed power factor, volt-var, ESC control functions evaluated with 6 controllable DER (orange)
- The global optimum was when all DER absorbed their rated reactive power
- VV did not reach the global optimum
- ESC tracked to the global optimum, but in much longer times than directly setting the fixed power factor




J. Johnson, et al, Experimental Distribution Circuit Voltage Regulation using DER Power Factor, Volt-Var, and Extremum Seeking Control Methods, IEEE PVSC, 2017.