Power Hardware-in-the-Loop Simulations of Distribution Circuit Voltage Regulation using Extremum Seeking Control

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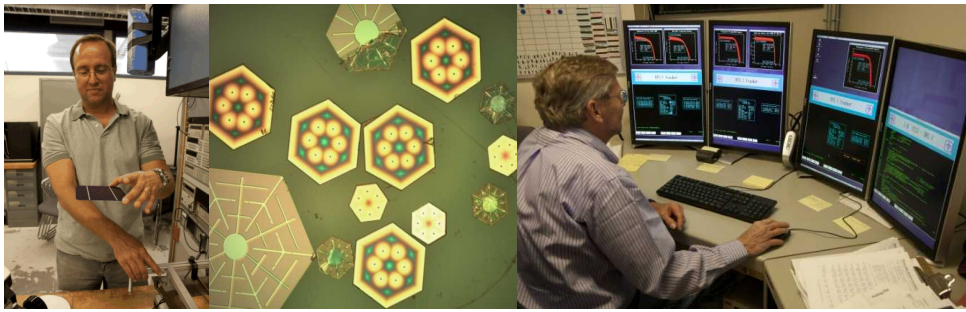

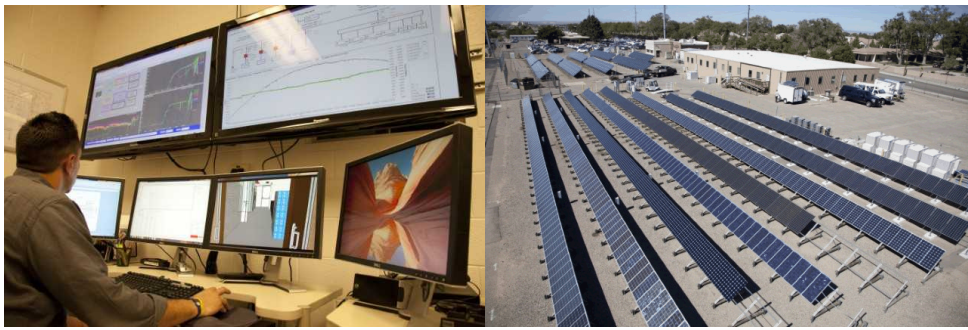

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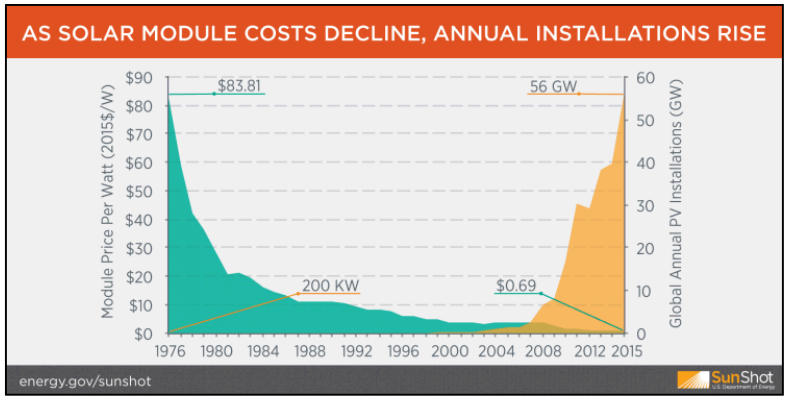
Background

- 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



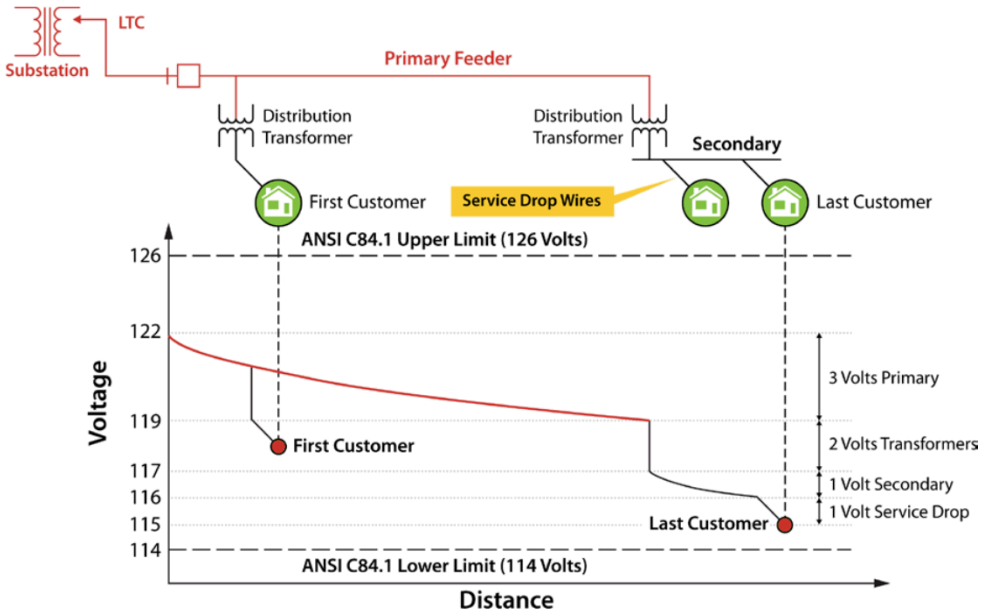
...Faster than a tap changer

...More powerful than a rotating machine

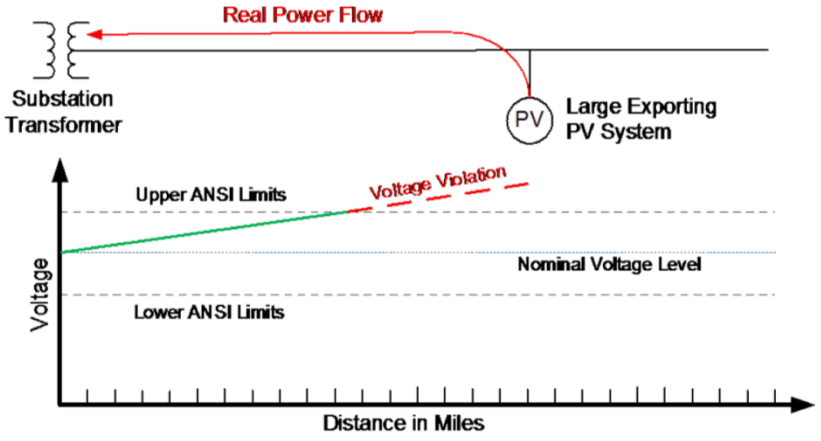
...Able to leap deep voltage sags in a single bound

Courtessy of B. Lydic, Fronius

Distribution Voltage Regulation



Voltage regulation on a feeder without distributed generation.



Voltage regulation on a feeder with distributed generation.

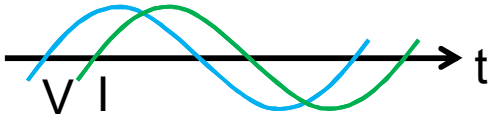
Solution: Use DER grid-support functions with reactive power capabilities.
- **Cost-effective: no additional equipment required**
- **Logical: employs devices which are causing voltage rise to mitigate the problem**

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.

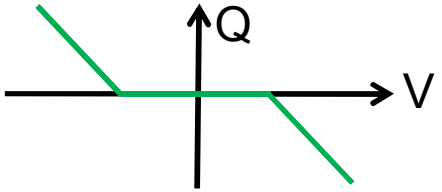
Options for Voltage Regulation using Grid-Support Functions

- **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, new inverter functionality

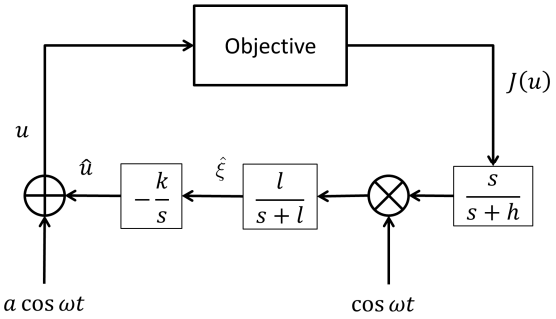
Adjust Power Factor



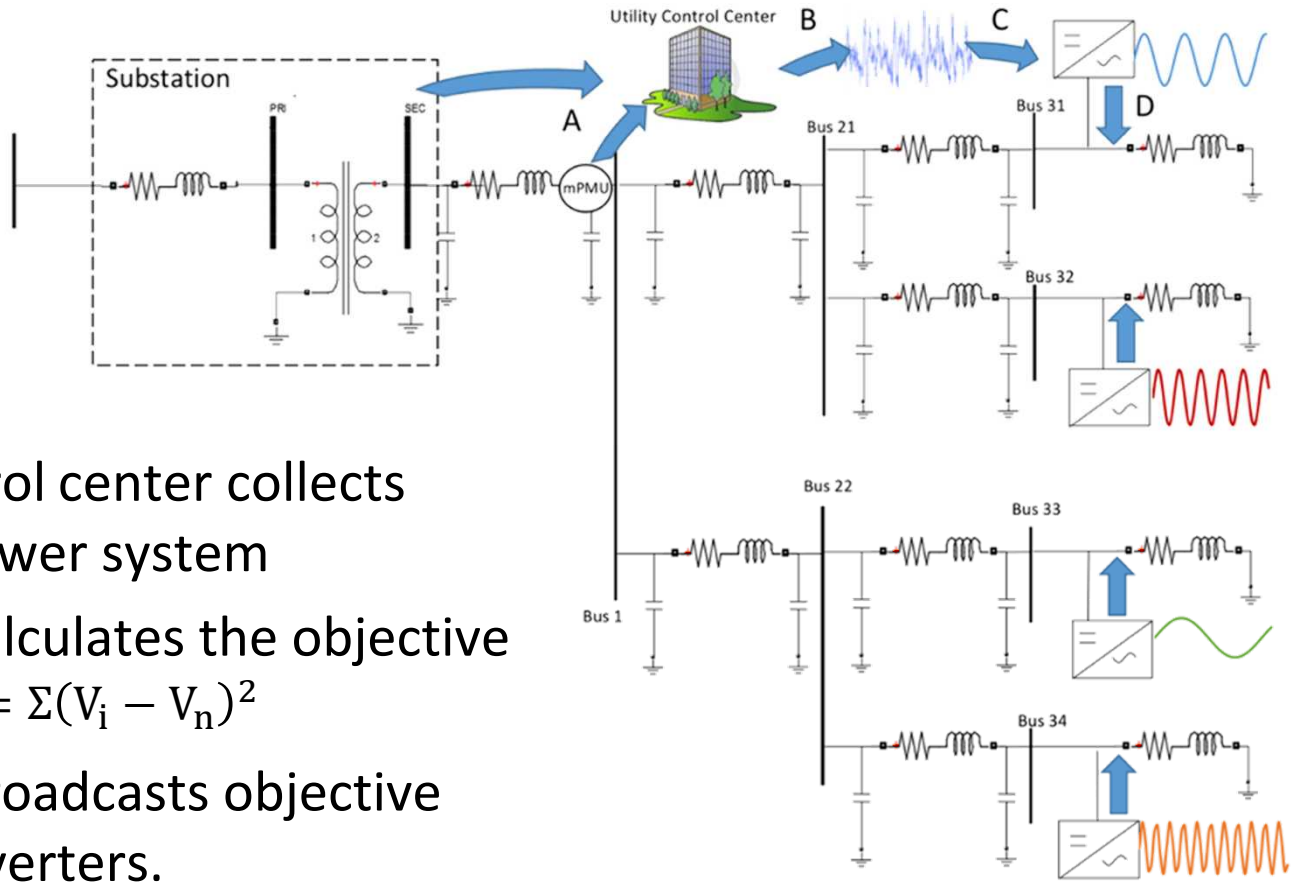
Volt-Var Mode



ESC



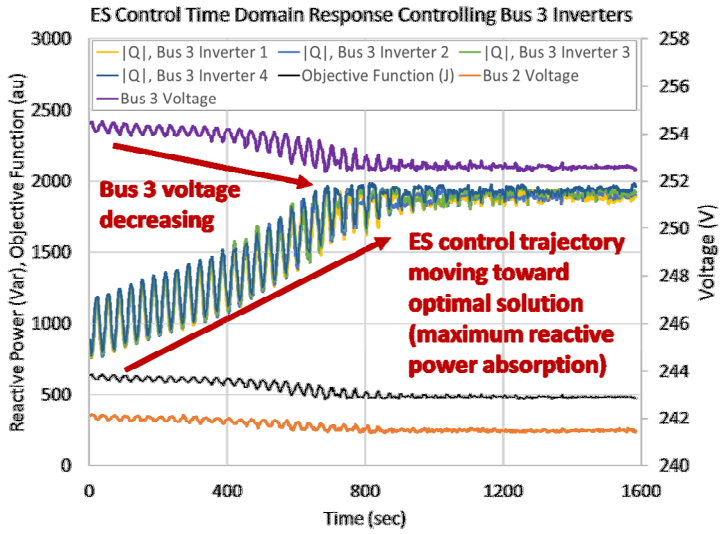
Extremum Seeking Control Steps

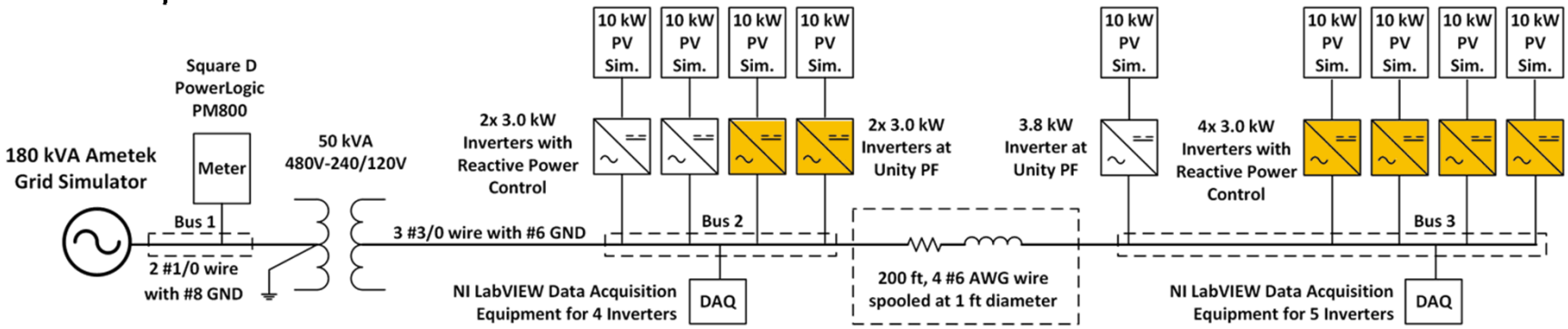


A. Centralized control center collects data from the power system
B. Control center calculates the objective function, e.g., $J = \Sigma(\mathrm{V_i} - \mathrm{V_n})^2$
C. Control center broadcasts objective function to all inverters.
D. Individual inverters extract their frequency-specific effect on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

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.

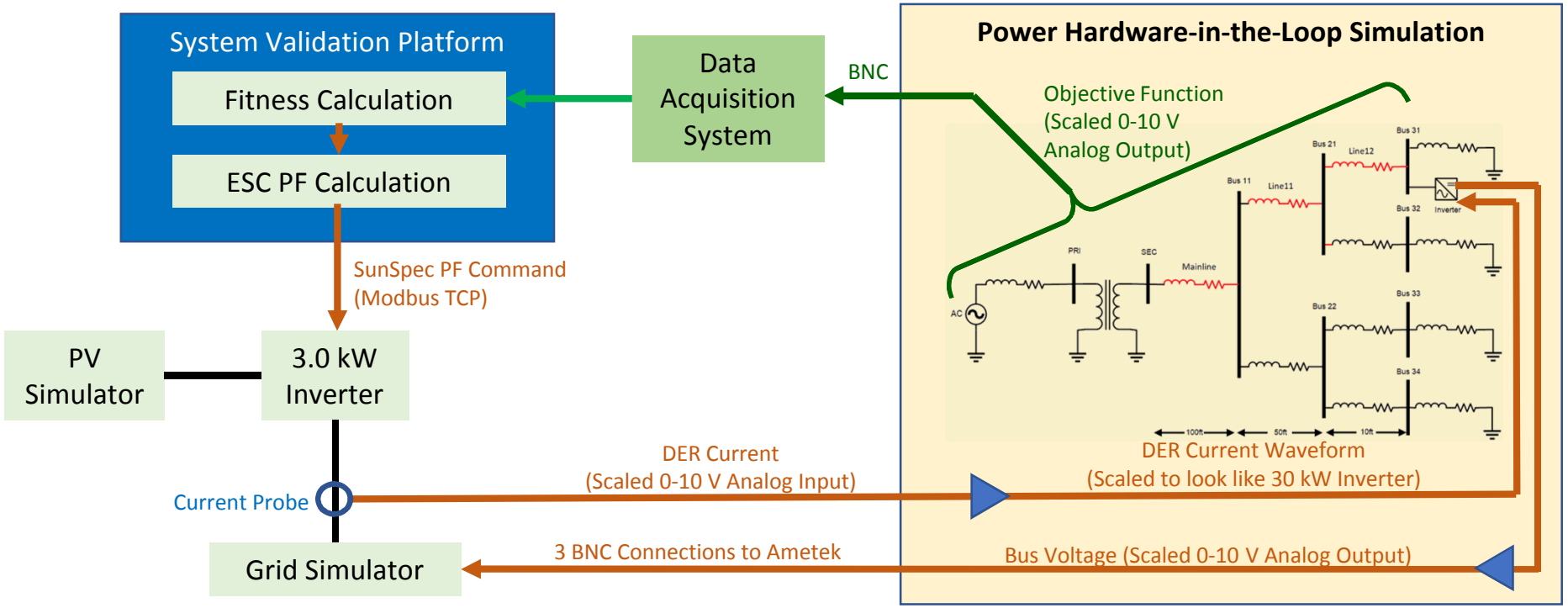




J. Johnson, et al, Experimental Distribution Circuit Voltage Regulation using DER Power Factor, Volt-Var, and Extremum Seeking Control Methods, IEEE PVSC, 2017.

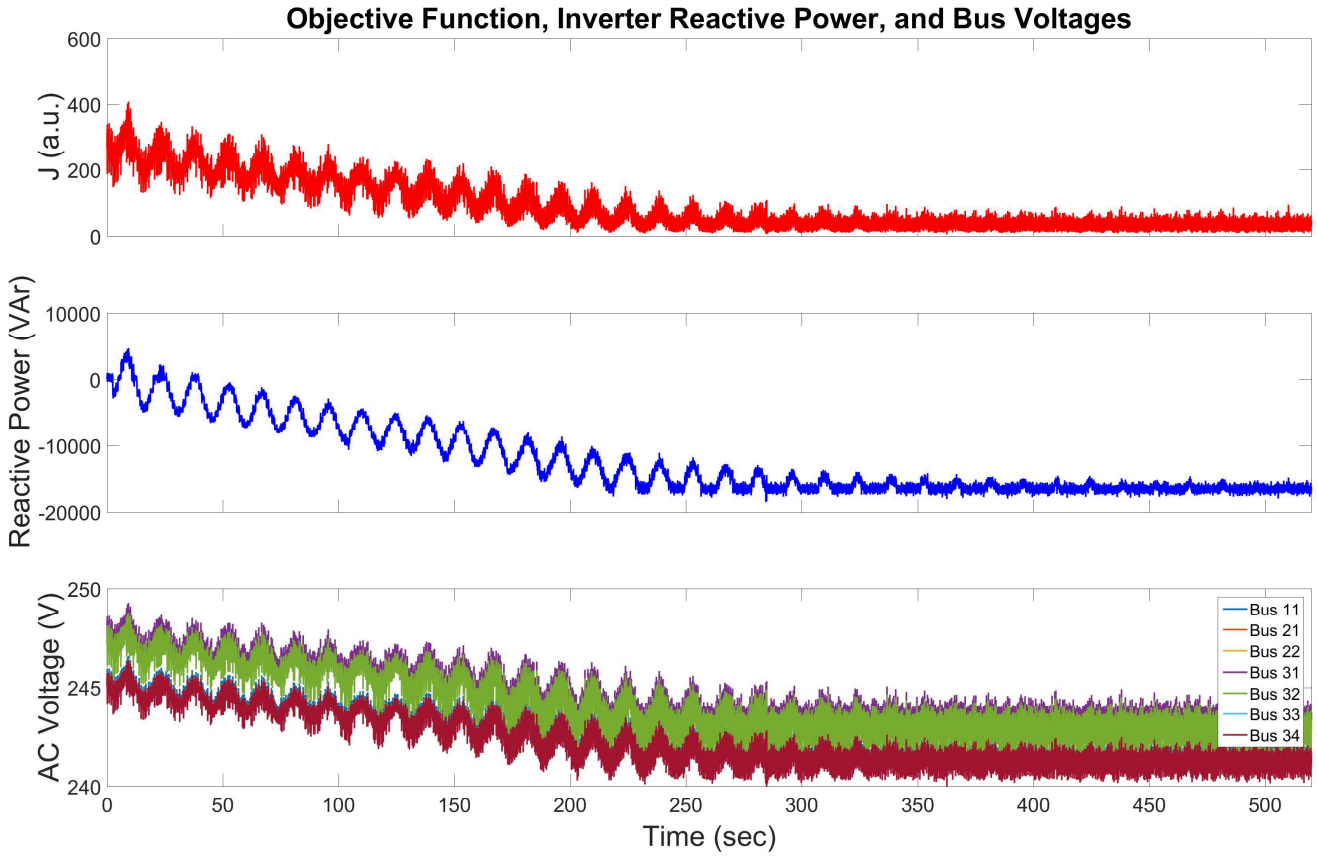
Current Work

- Team expanded ESC experiments to include an Opal-RT power hardware-in-the-loop (PHIL) system to simulate larger distribution circuits.



Preliminarily Results

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



Conclusions

- 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]
  - Protection assurance
  - Microgrid control
- Future work:
  - Study limitations of ESC with solar variability
  - Increase ESC response time of the control function
  - Run multiple inverters using simulated devices on the other buses
  - Run experiments using larger distribution circuit models from utilities.

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!

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