Phasor-Based Control

for Scalable Integration of Distributed Energy Resources

NASPI Work Group Meeting, April 2021

Alexandra "Sascha" von Meier

Adjunct Professor, Dept. of Electrical Engineering and Computer Science, UC Berkeley
Director, Electric Grid Research, California Institute for Energy and Environment
Faculty Scientist, Lawrence Berkeley National Laboratory, Grid Integration Group

vonmeier@berkeley.edu

California Institute for
Energy and Environment

Goals:

- Accelerate the transition to carbon-neutral energy
- Enhance electric grid reliability and resilience
- Remove barriers to the widespread adoption of solar PV generation and electric vehicles

Specific problem addressed here:

- Enabling distributed energy resources (PV, batteries, EV chargers and other controllable loads) to act as *good citizens* on the grid

Why is this hard?

- *Information* required to determine the right thing to do
- Response *speed* required to meaningfully support the grid

Research Team Members:

Elizabeth Ratnam, Keith Moffat, Jaimie Swartz, Jasper Pakshong, Gabe Fierro, Moustafa AbdelBaky, Leo Chu, Brittany Wais, Jiasheng Qin, T.G. Roberts, Daniel Tutt (UC Berkeley)

Christoph Gehbauer, Maxime Baudette, Evangelos Vrettos (Lawrence Berkeley Lab)

Dennis Bernstein, Aseem Ul Islam, Adam Bruce (Univ. of Michigan)

Ravi Venugopal, Sudipta Chakraborty, Guna Bharati (OPAL-RT)

Kevin D. Jones (Dominion Energy and Gridwidget Labs)

Terry Nielsen, Shangyou Hao (GridBright)

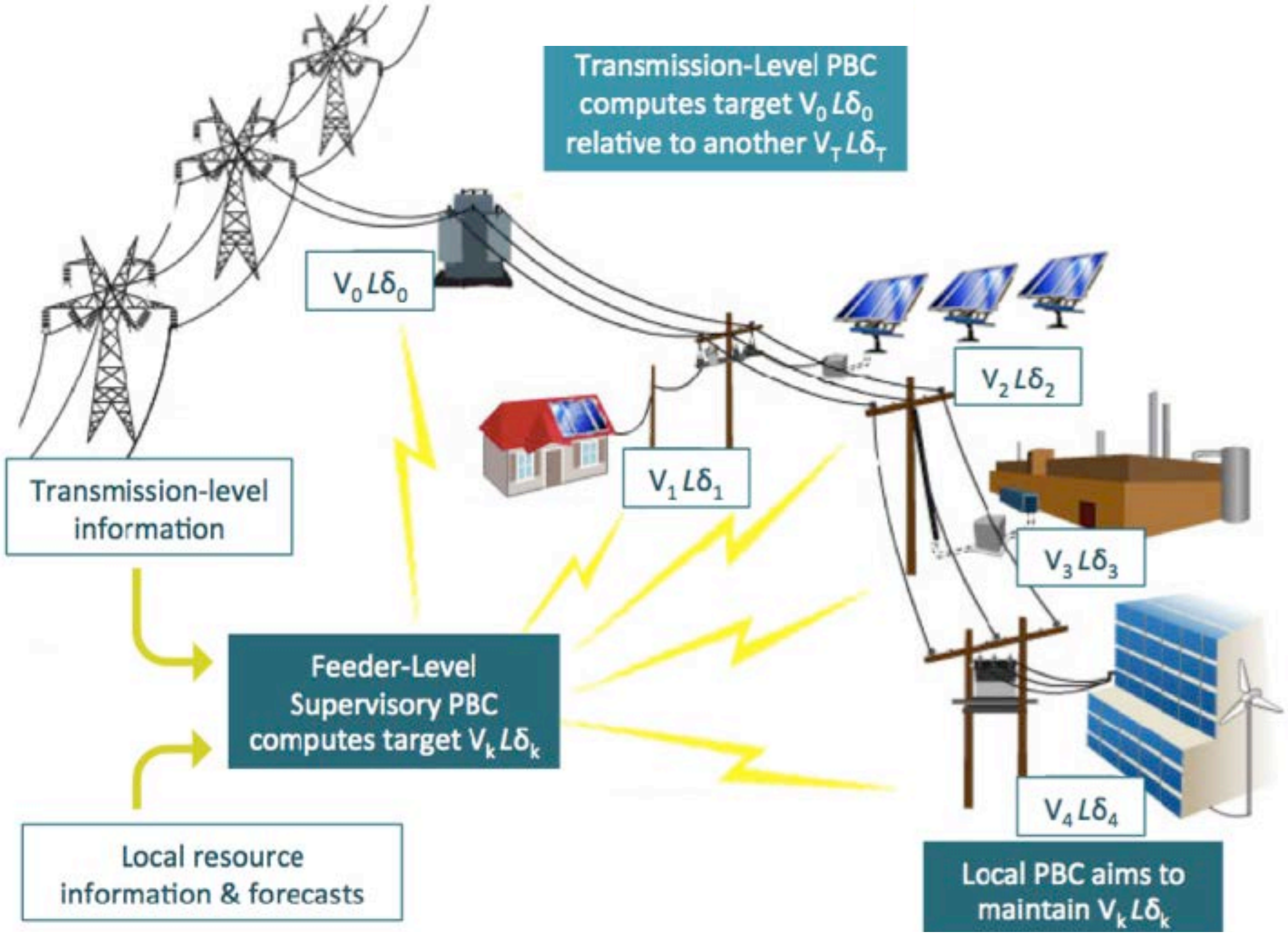
Sean Murphy (PingThings)

Harby Sehmar (PG&E)

Phasor-Based Control

Concept developed and proven in recent DOE SETO funded project (DE-EE0008008) led by UC Berkeley/CIEE with

Project partners: Lawrence Berkeley Lab, Univ. of Michigan, OPAL-RT, GridBright, PingThings, PG&E



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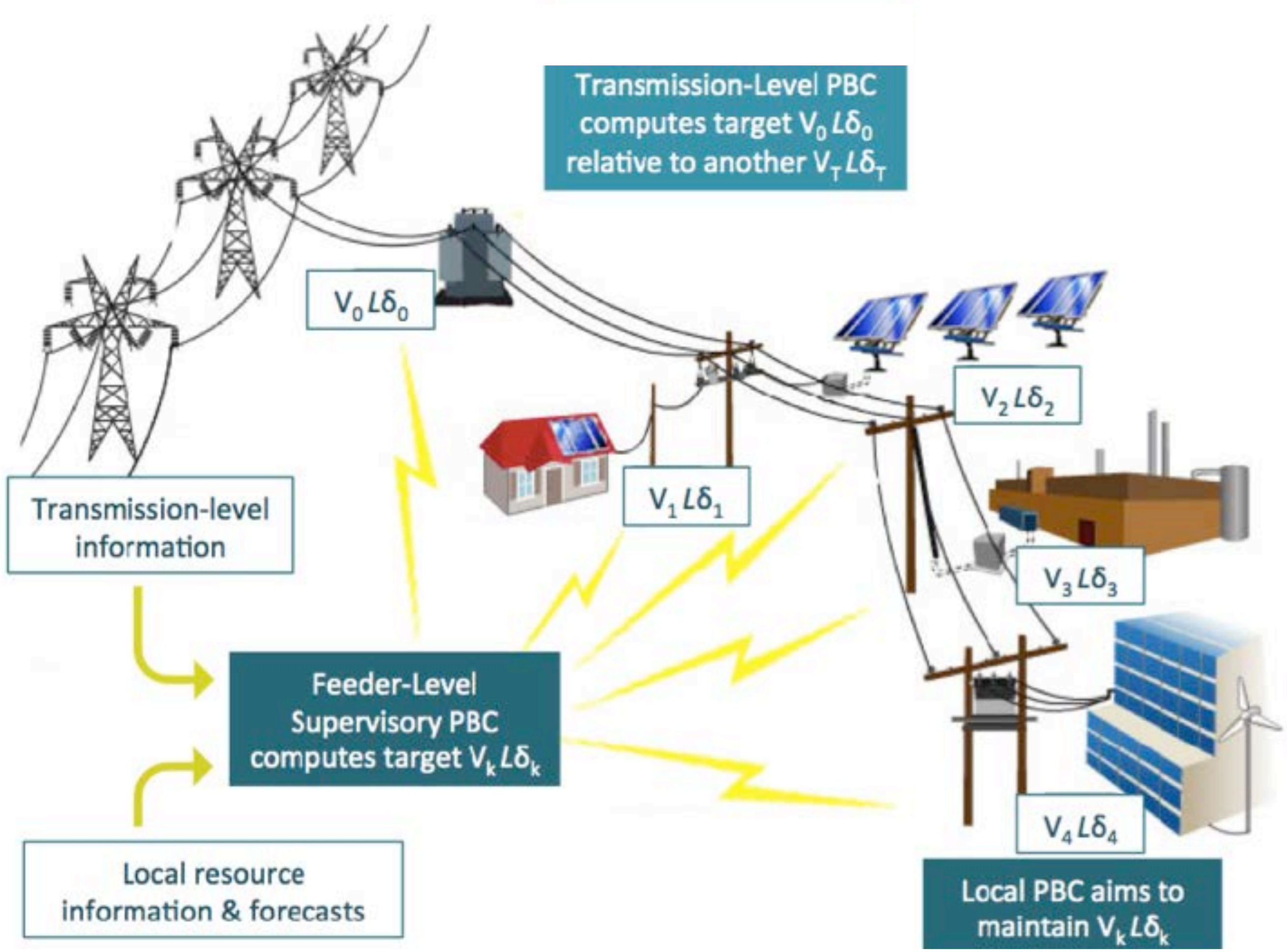


Phasor-Based Control

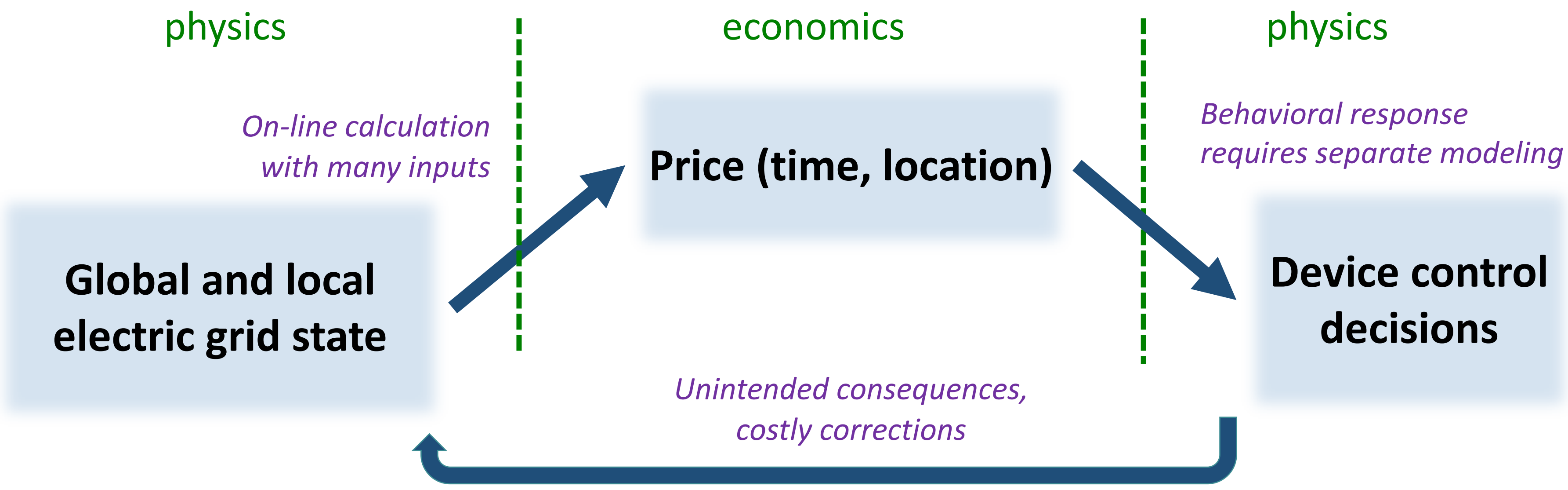
In PBC, resources act to maintain a target voltage phasor (magnitude and angle) difference between a pair of locations.

As state variables, voltage phasors encapsulate all information about power flow (real and reactive).

Hierarchical layers:

- Supervisory PBC computes phasor control targets at chosen nodes
- Local PBC drives resources to meet targets

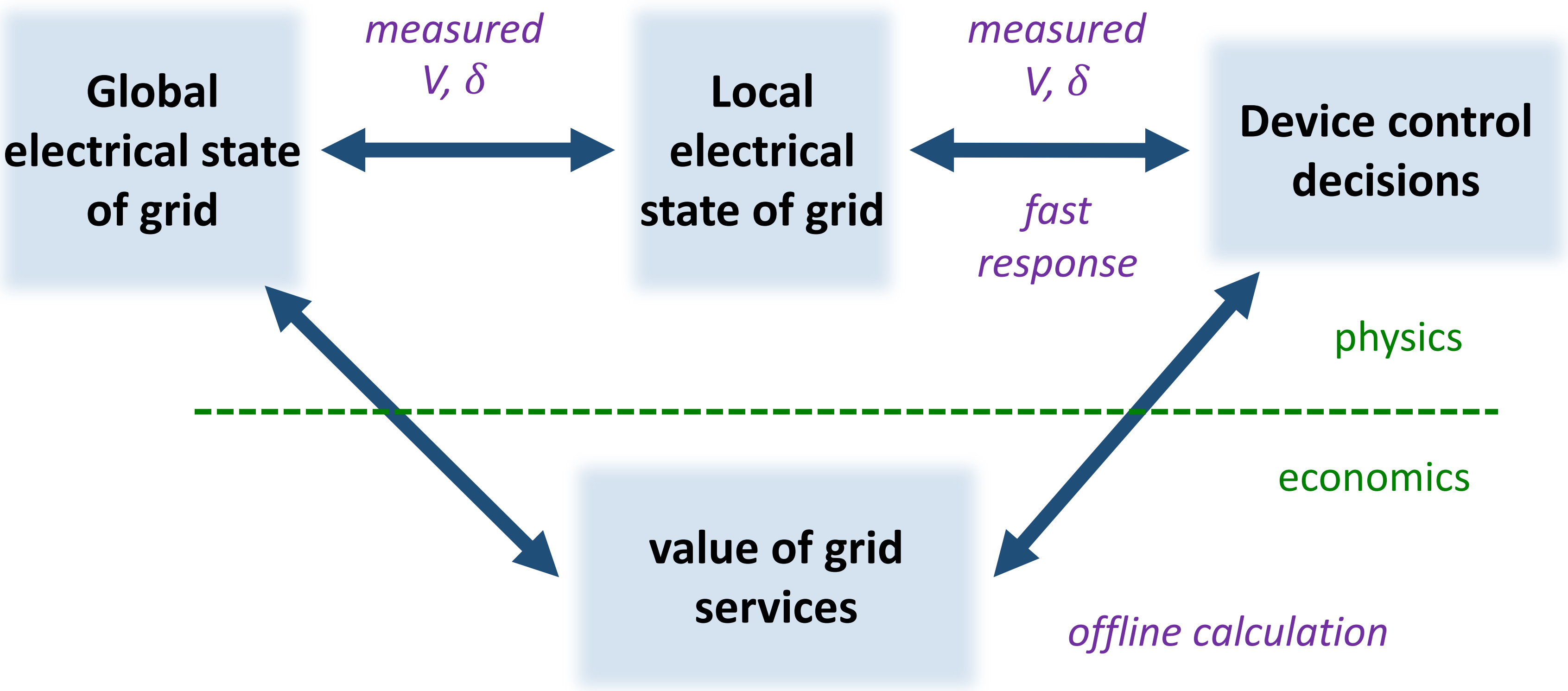
Conventional Wisdom: Price-Based Control



Problems with extending this paradigm from transmission to distribution systems:

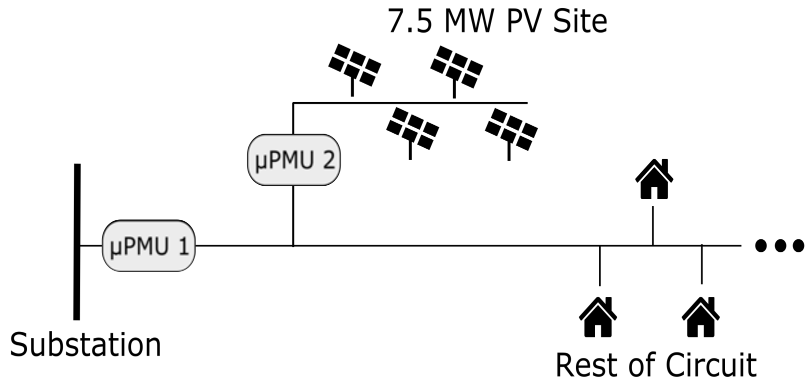
- *Lacking model information*
- *Phase Imbalance*
- *Complexity of locational pricing*

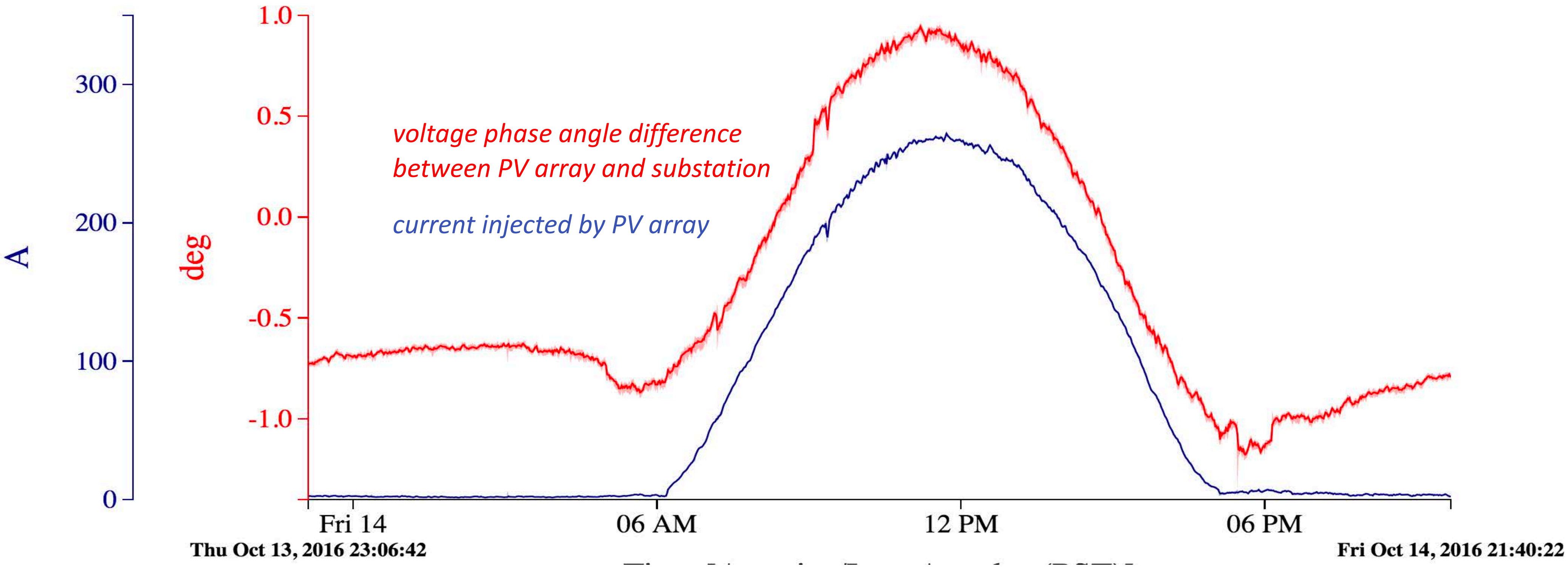
Phasor-Based Control Concept



Enabling Technology: µPMU

Voltage magnitudes and phase angle differences can be measured with meaningful precision for distribution power flows.





Relationships between voltage phasor and distribution power flow

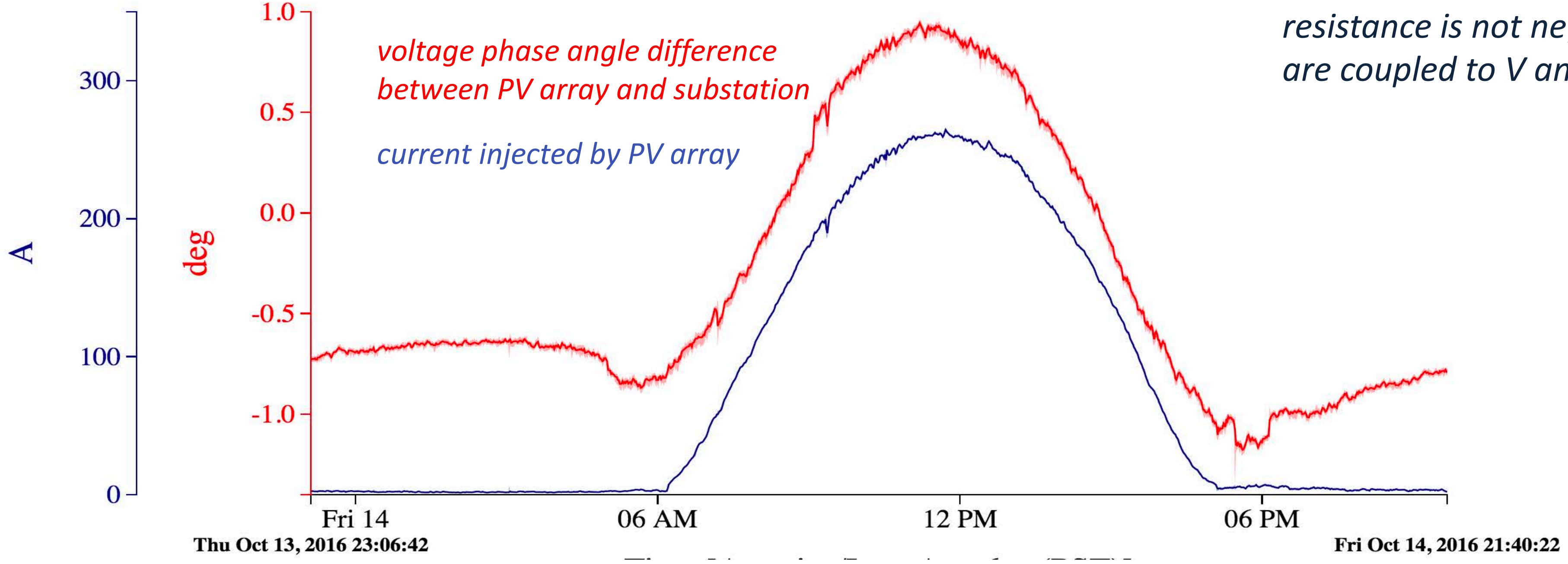
$$P_{12} \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$

Transmission system approximation, where reactance dominates over resistance (X >> R)

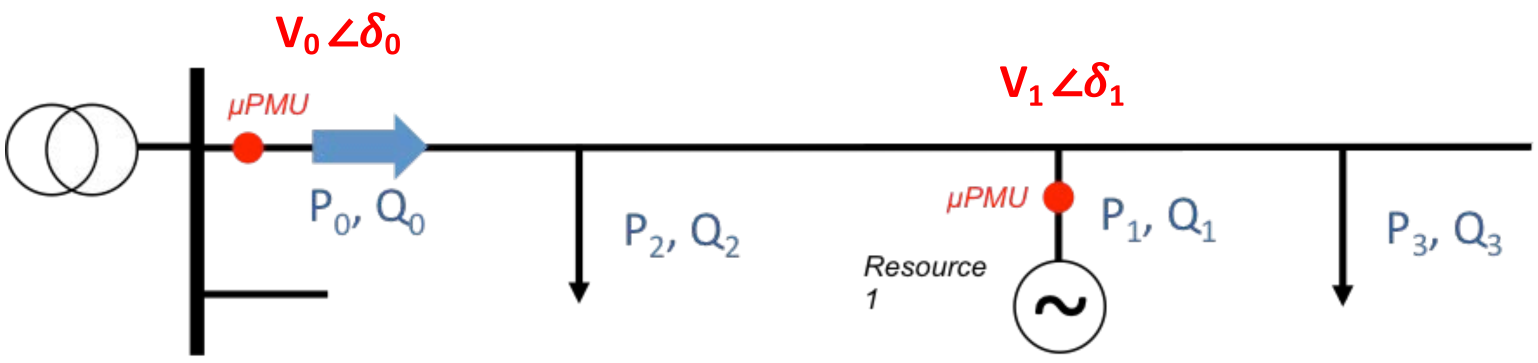
$$|V_1|^2 - |V_2|^2 \approx 2(RP + XQ)$$

$$\delta_1 - \delta_2 \approx \frac{XP - RQ}{|V_1|\,|V_2|}$$

Distribution system approximation, where resistance is not negligible and both P and Q are coupled to V and δ



Motivating Intuition for Phasor-Based Control



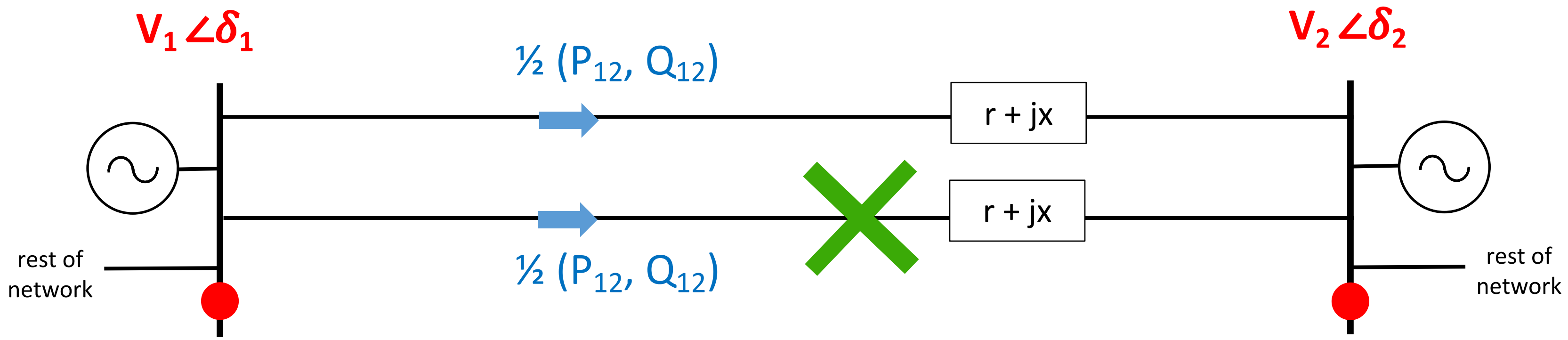
What should Resource 1 be doing?

The desired injection P_1, Q_1 depends on the behavior of loads, other DER and network topology.

Phasor profile ***$V_0 - V_1$***

- reflects changes in P_2, Q_2 and P_3, Q_3 whereas net power P_0, Q_0 may not
- reflects changes in topology whereas net power P_0, Q_0 may not
- remains relevant to local operating constraints
- helps co-optimize real and reactive power
- allows resources to respond directly to behavior of other DERs without compromising privacy

Motivating Intuition for Phasor-Based Control



How should Resource 2 respond to a contingency?

If one transmission line fails, the network impedance between 1 and 2 will roughly double

Scheduled power flows P_{12} , Q_{12} may exceed thermal or stability limits of the remaining line

Resource 2 has no way of knowing whether its scheduled P, Q injection is still safe for the grid

However: The profile $V_1 - V_2$ *instantly* reveals stress on the transmission path

By tracking the phasor difference, Resource 2 restores power flow on the remaining line to the previous value of ½ (P_{12} , Q_{12})

Supervisory Phasor-Based Controller (S-PBC) assigns phasor targets

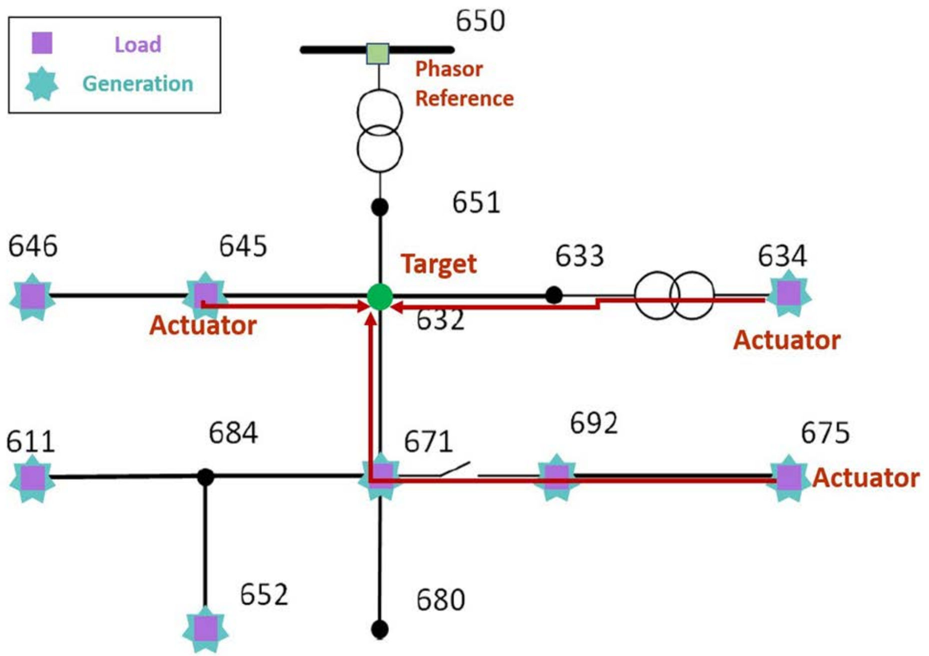
Supervisory controller performs a power flow optimization, whose results it expresses in terms of target phasors at performance nodes

- *PBC is agnostic to the optimization criteria*
- *Optimization time step may be seconds or minutes*

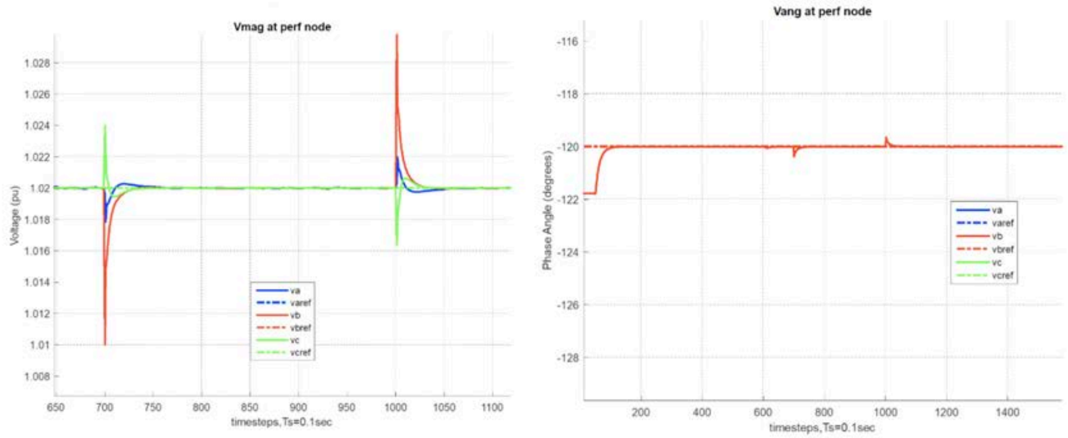
S-PBC uses a suitable compromise between full nonlinear and linearized power flow for computational efficiency

Test cases studied:

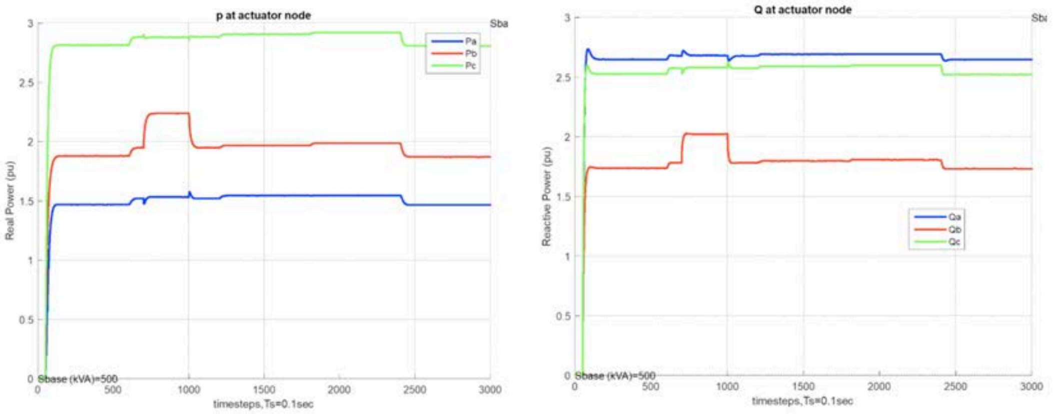
- *Net power flow control at feeder head*
- *ABC phase balancing*
- *Voltage volatility management*
- *Phasor matching to support switching operations*
- *N-1 security enhancement for transmission level*



Local Phasor-Based Controller (L-PBC) tracks phasor targets



Voltage magnitude (left) and phase angle (right) tracking by a three-phase local controller in response to a large step change in load elsewhere on the same distribution circuit



Actuation effort in real (left) and reactive (right) power to produce above results under PI control
Note different time scales in the two sets of graphs.

Local controller recruits one or multiple distributed energy resources

- *actuators may include PV inverters, storage, controllable loads*
- *may be single- or three-phase*
- *may provide real and/or reactive power*

Simulations show tracking phasor target, rejecting disturbances with control time step ~ 0.5 to 1 sec

Multiple L-PBC algorithms were created and tested:

- *Proportional-Integral (PI) Controller*
- *Linear Quadratic Regulator*
- *Retrospective Cost Adaptive Controller*

J. Swartz, T.G. Roberts, A. von Meier and E. Ratnam, "Local Phasor-Based Control of DER Inverters for Voltage Regulation on Distribution Feeders." IEEE GreenTech Conference, Oklahoma City, OK, April 2020.

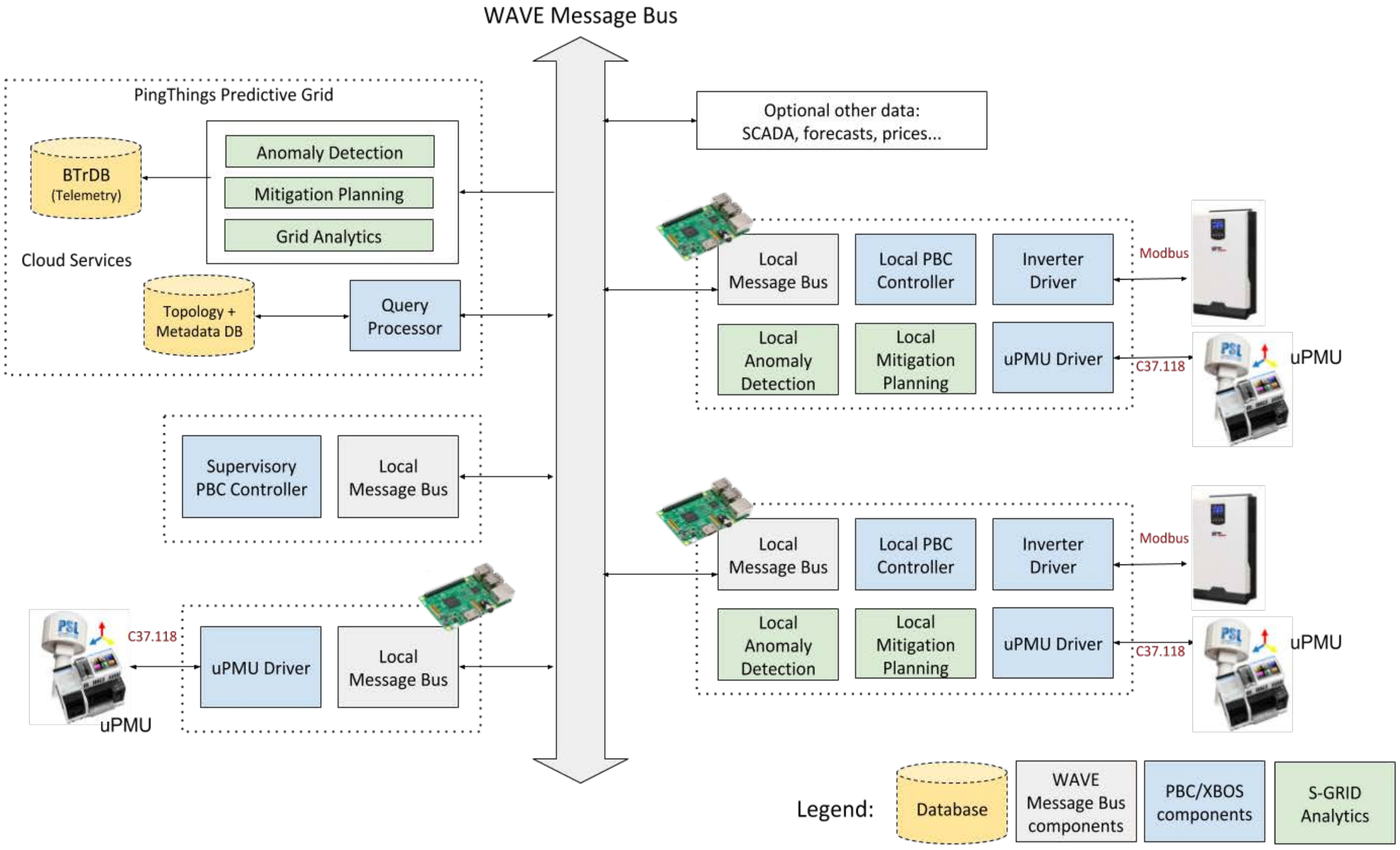
HIL Testing at Berkeley Lab's FLEXGRID

FLEXGRID HIL testing setup. © 2010-2019 The Regents of the University of California, Lawrence Berkeley National Laboratory. Photo Credit: Thor Swift.

HIL Testing at Berkeley Lab's FLEXGRID

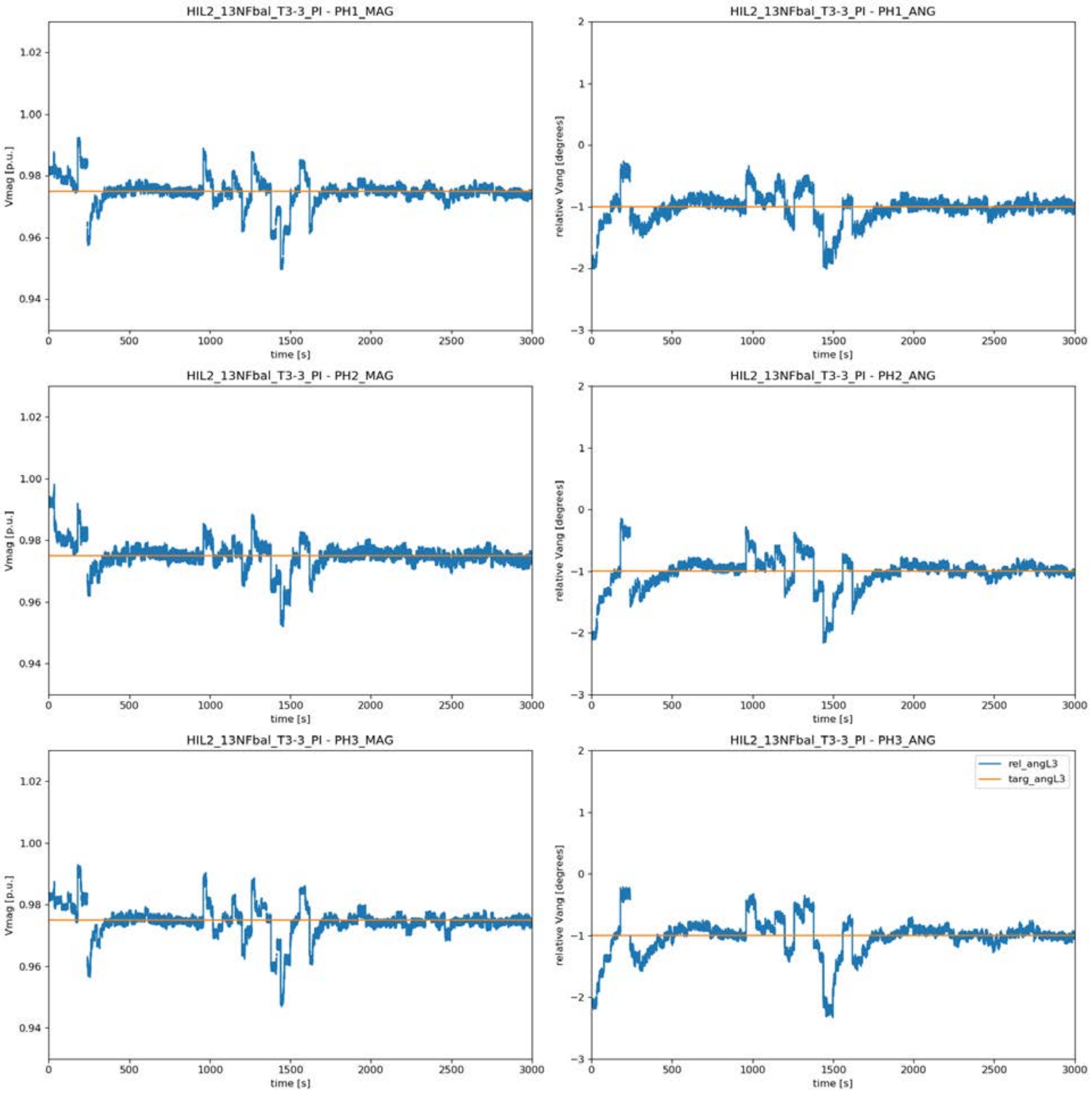
Maxime Baudette with micro-PMUs at the FLEXGRID. Photo Credit: Thor Swift.

Extensible Data Infrastructure



Publish-subscribe message bus supports secure communication of sensitive grid data with decentralized authorization among multiple actors

G. Fierro, K. Moffat, J. Pakshong and A. von Meier, "An Extensible Software and Communication Platform for Distributed Energy Resource Management." IEEE SmartGridComm'20, November 11-13 2020.

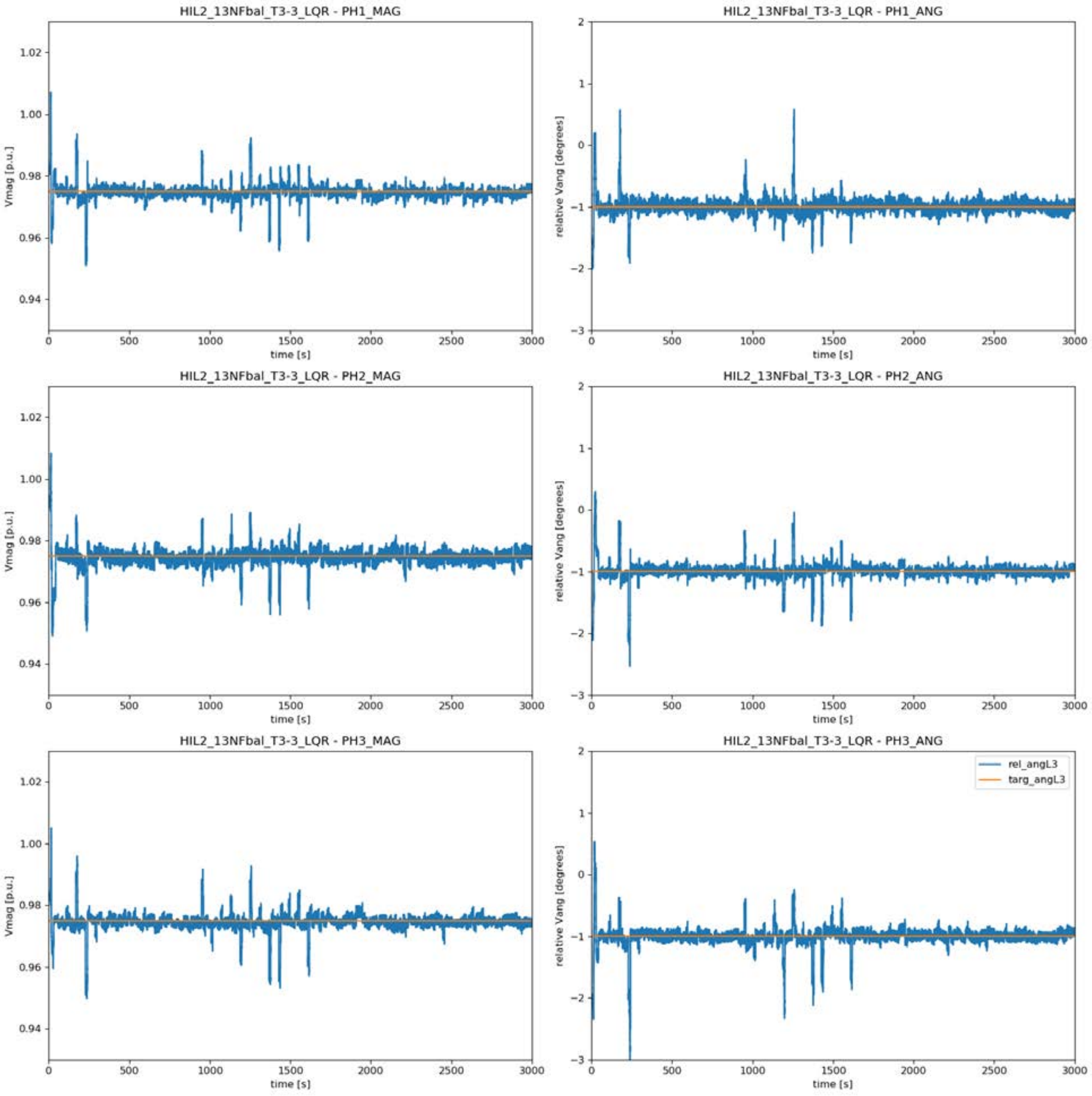


Sample HIL Test results

Inverters are recruited to reject large disturbances from time-varying loads on all three phases using **PI** control logic.

Phasor tracking results from HIL Test 3.3, showing magnitude (left) and angle (right) on each phase at performance node 675, with co-located actuators.

The yellow line indicates the phasor target for node 675, with the reference phasor 1.0 p.u. and 0^{o} at the feeder head.

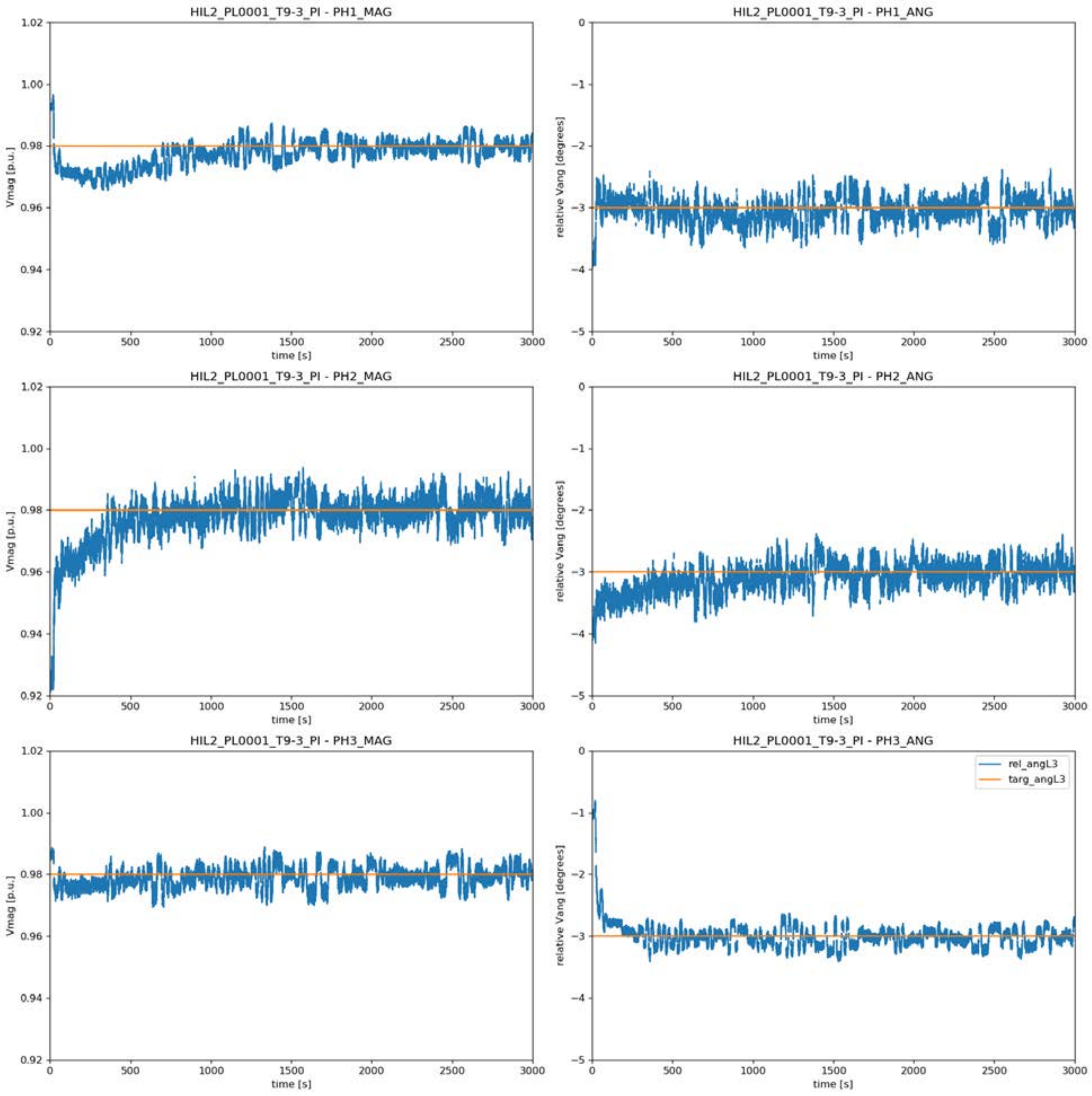


Sample HIL Test results

Inverters are recruited to reject large disturbances from time-varying loads on all three phases using **LQR** control logic.

Phasor tracking results from HIL Test 3.3, showing magnitude (left) and angle (right) on each phase at performance node 675, with co-located actuators.

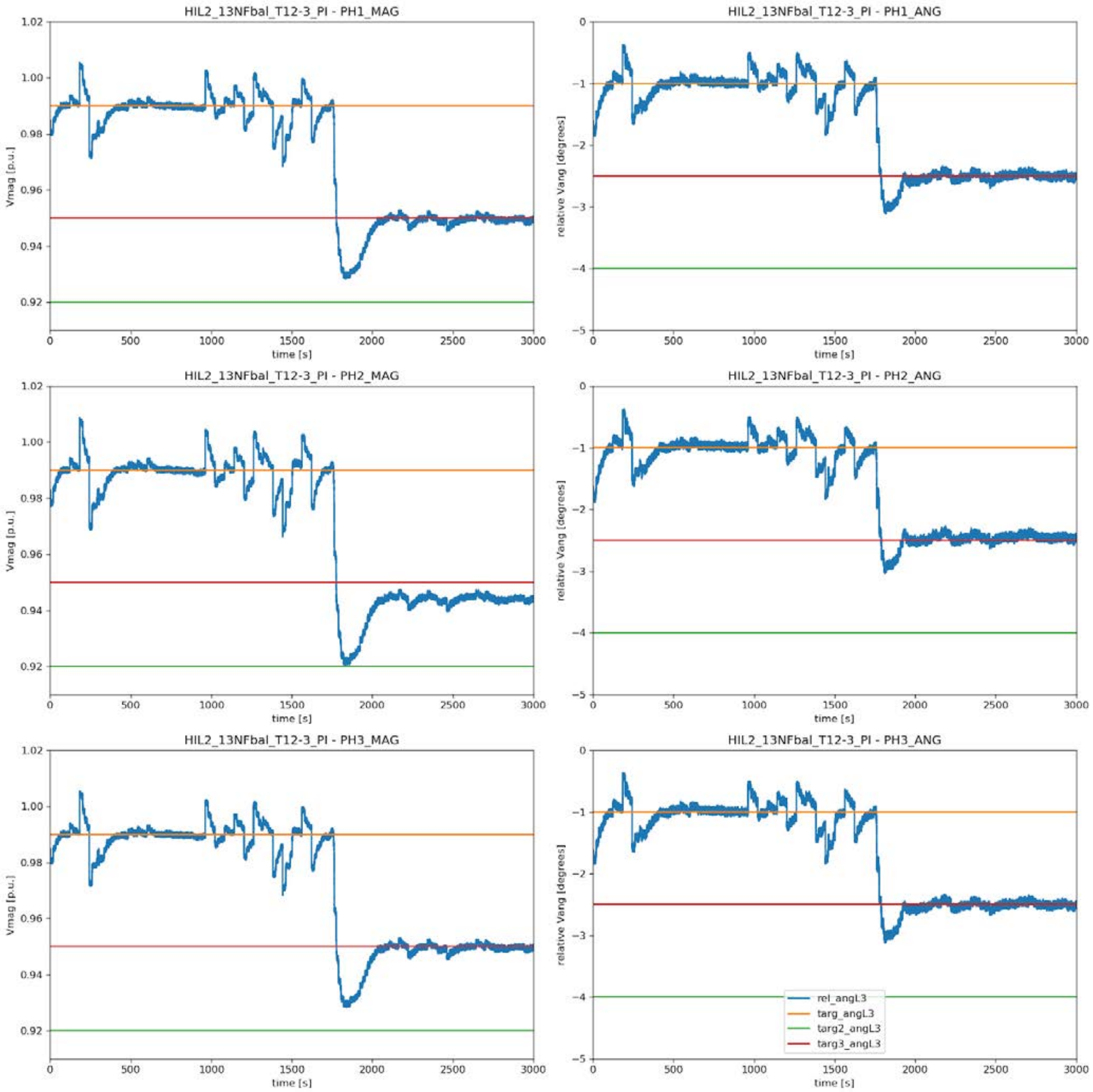
The yellow line indicates the phasor target for node 675, with the reference phasor 1.0 p.u. and 0^o at the feeder head.



Sample HIL Test results

Inverters recruited to track target on PG&E feeder PL0001 in the presence of highly variable loads and high PV penetration.

Controller tracks target (yellow) on a large feeder with high second-wise load variance.



Sample HIL Test results

Local and supervisory controllers successfully re-negotiate an unrealistic phasor target

Test scenario 12-3 on the 13-node balanced feeder, showing the controller recovering from the "I Can't Do It" condition.

Challenges

✓ Conditioning of the problem

- small phasor differences correspond to large power injections
- requires ultra-precise measurement; useful size for actuators is ~100 kW

✓ Supervisory controller computational speed vs. target accuracy

- various optimal power flow linearization approaches are workable
- our team developed a loss-approximation OPF method and iterative procedure for S-PBC

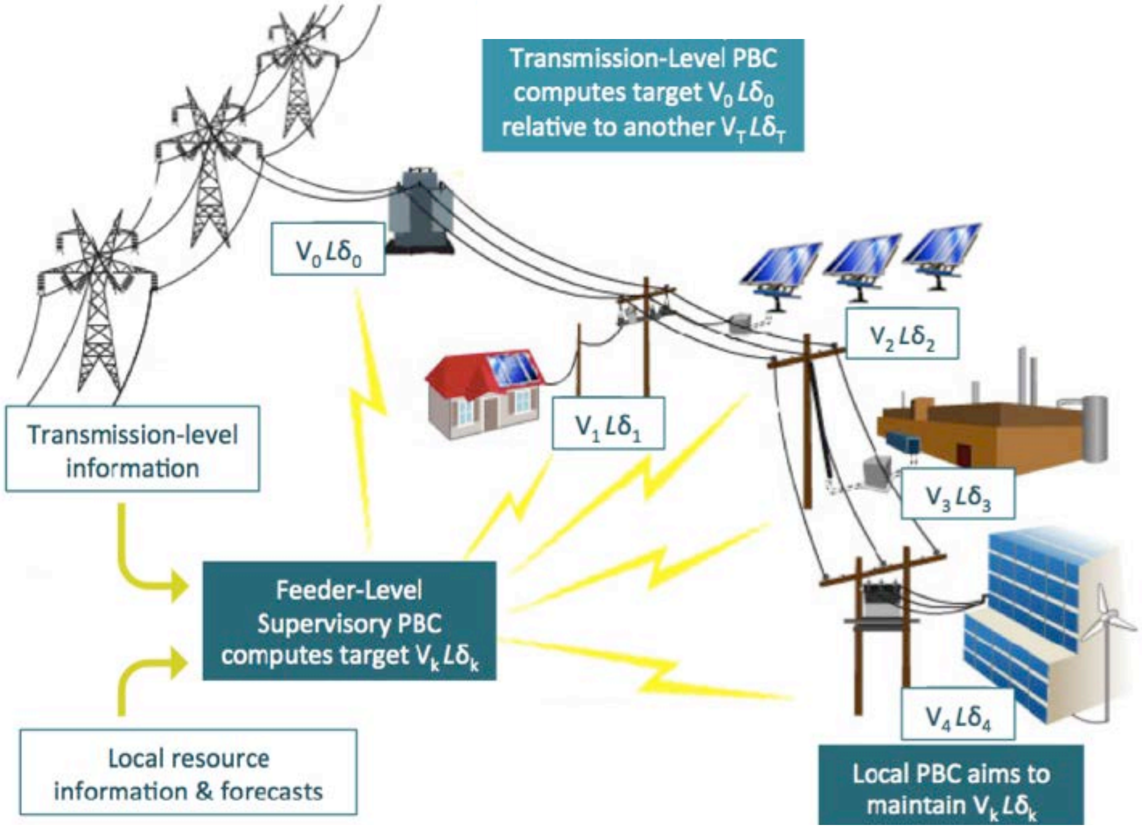
✓ Local controller performance vs. need for network model

- PI and RCAC (SISO) algorithms work without a distribution circuit model but can be confounded by R/X ratio and phase coupling
- LQR (MIMO) is very fast and robust but requires a network model

✓ Scaling

- large feeders with multiple actuator and performance nodes are manageable
- Layering into transmission network appears feasible

❑ Explicit P-Q control access to inverters is a significant practical limitation



Conclusion

We established that under PBC, multiple and diverse distributed energy resources can:

- track voltage phasor targets to within 0.005 per-unit
- reject step disturbances in neighboring net loads of up to 100% of their capacity
- help the manage power flows and volatility on the grid

The PBC paradigm can be physically implemented with secure communications, robust to failures.

Next: Field demo!

PBC Publications

1. A. Ul Islam, E. Ratnam and D. Bernstein, "Phasor-Based Adaptive Control of a Test-Feeder Distribution Network." IEEE Transactions on Control Systems, 2019.
2. A. von Meier, E. Ratnam, K. Brady, K. Moffat and J. Swartz, "Phasor-Based Control for Scalable Integration of Variable Energy Resources." *Energies* 2020, 13(1), 190. https://doi.org/10.3390/en13010190
3. K. Moffat, M. Bariya and A. von Meier, "Real Time Effective Impedance Estimation for Power System State Estimation." IEEE Innovative Smart Grid Technologies (ISGT) Conference, Washington, DC, Feb 2020.
4. J. Swartz, T.G. Roberts, A. von Meier and E. Ratnam, "Local Phasor-Based Control of DER Inverters for Voltage Regulation on Distribution Feeders." *IEEE GreenTech Conference*, Oklahoma City, OK, April 2020.
5. K. Moffat, M. Bariya and A. von Meier, "Unsupervised Impedance and Topology Estimation of Distribution Networks—Limitations and Tools." *IEEE Transactions on Smart Grid* 2020, 11(1).
6. G. Fierro, K. Moffat, J. Pakshong and A. von Meier, "An Extensible Software and Communication Platform for Distributed Energy Resource Management." IEEE SmartGridComm'20, November 11-13 2020.
7. K. Brady and A. von Meier, "Iterative Linearization for Phasor-Defined Optimal Power Dispatch." North American Power Symposium (NAPS), Tempe AZ, April 2021.
8. J. Swartz, B. Wais, E. Ratnam and A von Meier, "Visual Tool for Assessing Stability of DER Configurations on Three-Phase Radial Networks." Submitted to IEEE Powertech 2021. arXiv preprint available at arXiv:2011.07232
9. K. Moffat, J. Pakshong, L. Chu, G. Fierro, J. Swartz, M. Baudette, C. Gehbauer and A. von Meier, "Phasor-Based Control with the Distributed, Extensible Grid Control Platform."
10. M. Baudette, L. Chu, C. Gehbauer, K. Moffat, J. Pakshong, J. Swartz and A. von Meier, "Hardware in the Loop Benchmarking for Phasor-Based Control Validation." (in preparation)
11. K. Moffat and A. von Meier, "Local Power-Voltage Sensitivity and Thévenin Impedance Estimation from Phasor Measurements." (in preparation)

Questions?

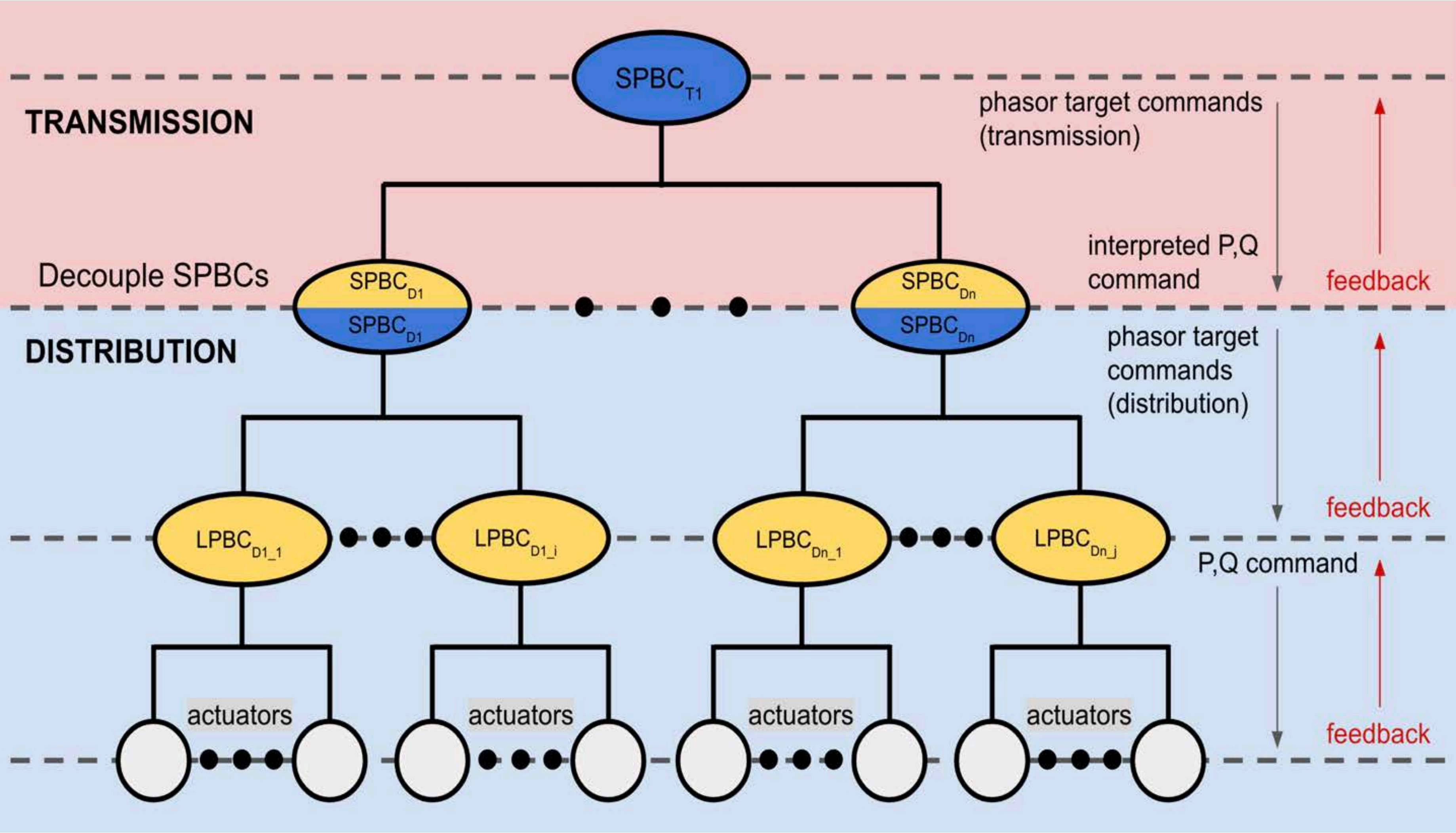
Alexandra “Sascha” von Meier

Adjunct Professor, Dept. of Electrical Engineering and Computer Science, UC Berkeley
Director, Electric Grid Research, California Institute for Energy and Environment
Faculty Scientist, Lawrence Berkeley National Laboratory, Grid Integration Group

vonmeier@berkeley.edu

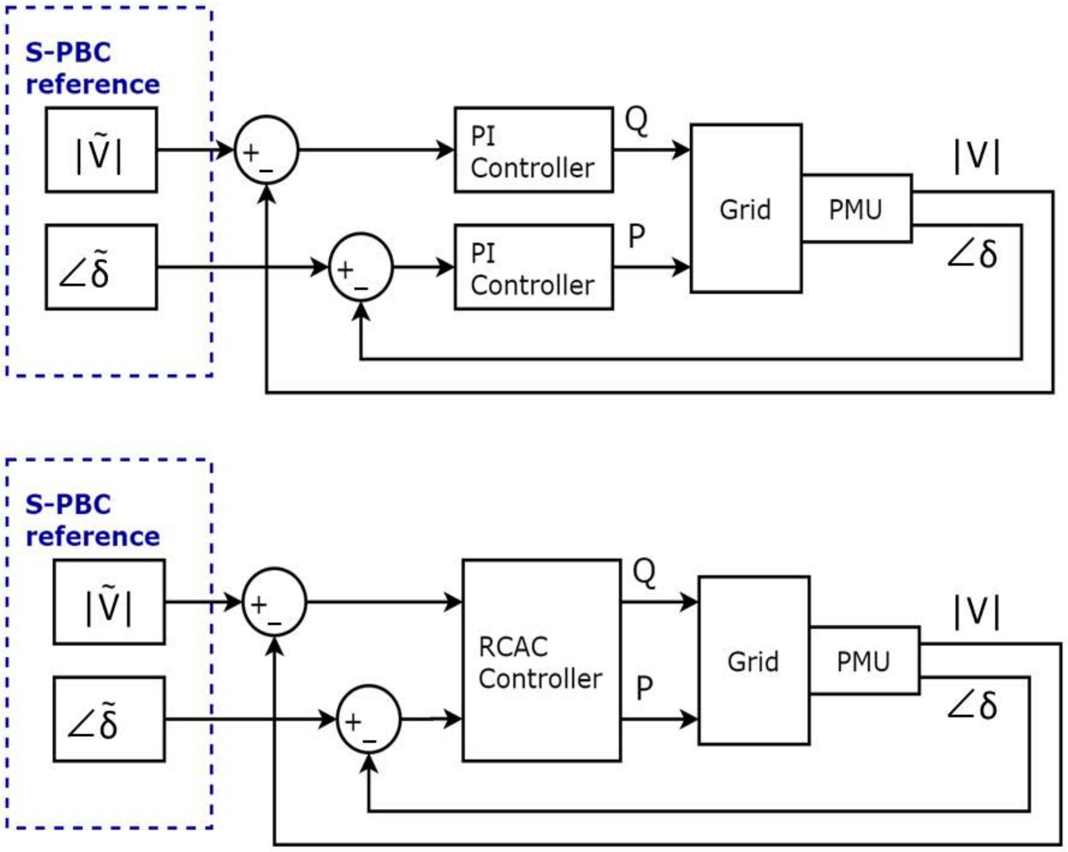
Extra slides

PBC Scaling



TRANSMISSION
SPBC$_{T1}$
phasor target commands (transmission)
interpreted P,Q command
feedback
Decouple SPBCs
SPBC$_{D1}$
SPBC$_{D1}$
SPBC$_{Dn}$
SPBC$_{Dn}$
DISTRIBUTION
phasor target commands (distribution)
feedback
LPBC$_{D1_1}$
LPBC$_{D1_i}$
LPBC$_{Dn_1}$
LPBC$_{Dn_j}$
P,Q command
actuators
actuators
actuators
actuators
feedback

Local Controller Architectures



Block diagram for the SISO (top) and MIMO (bottom) control architectures

Linear Quadratic Regulator for PBC

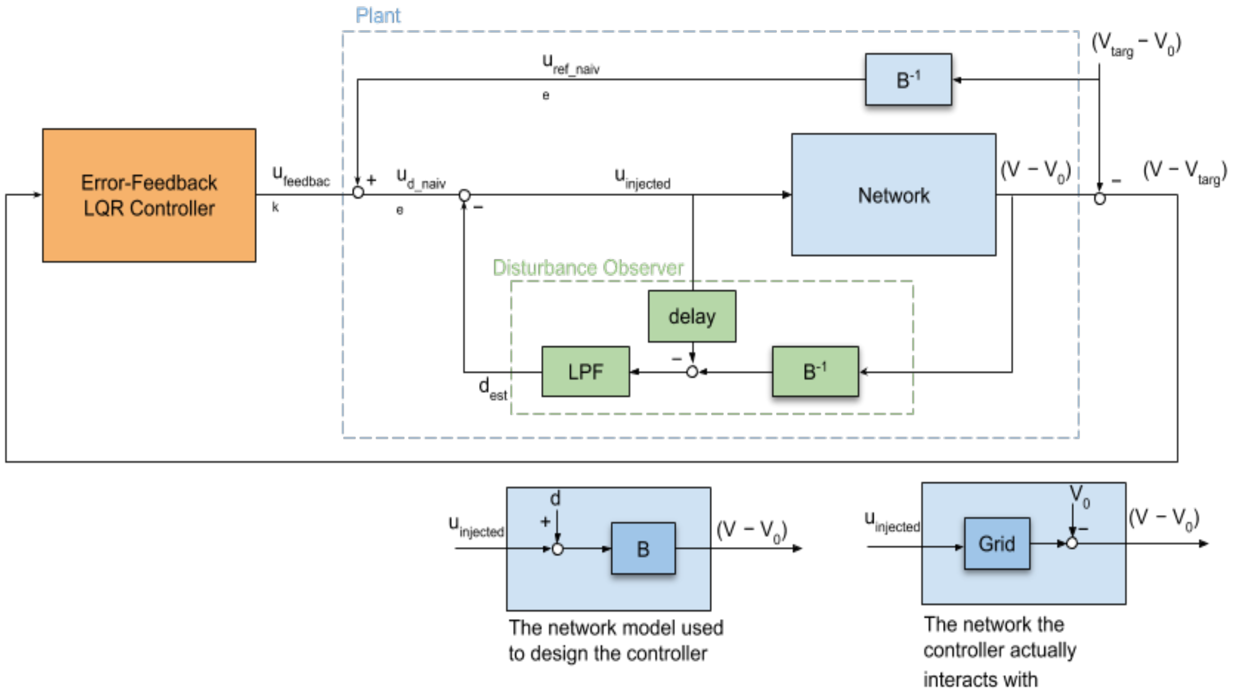
The LQR controller contains both a linear, MIMO Feedback policy, and an internal Disturbance Cancellation loop.

MIMO Feedback Policy:

- Determined by the standard LQR equations, using a linearized power flow model for the network
- Includes both error and error-integrating states, to account for model mismatch.

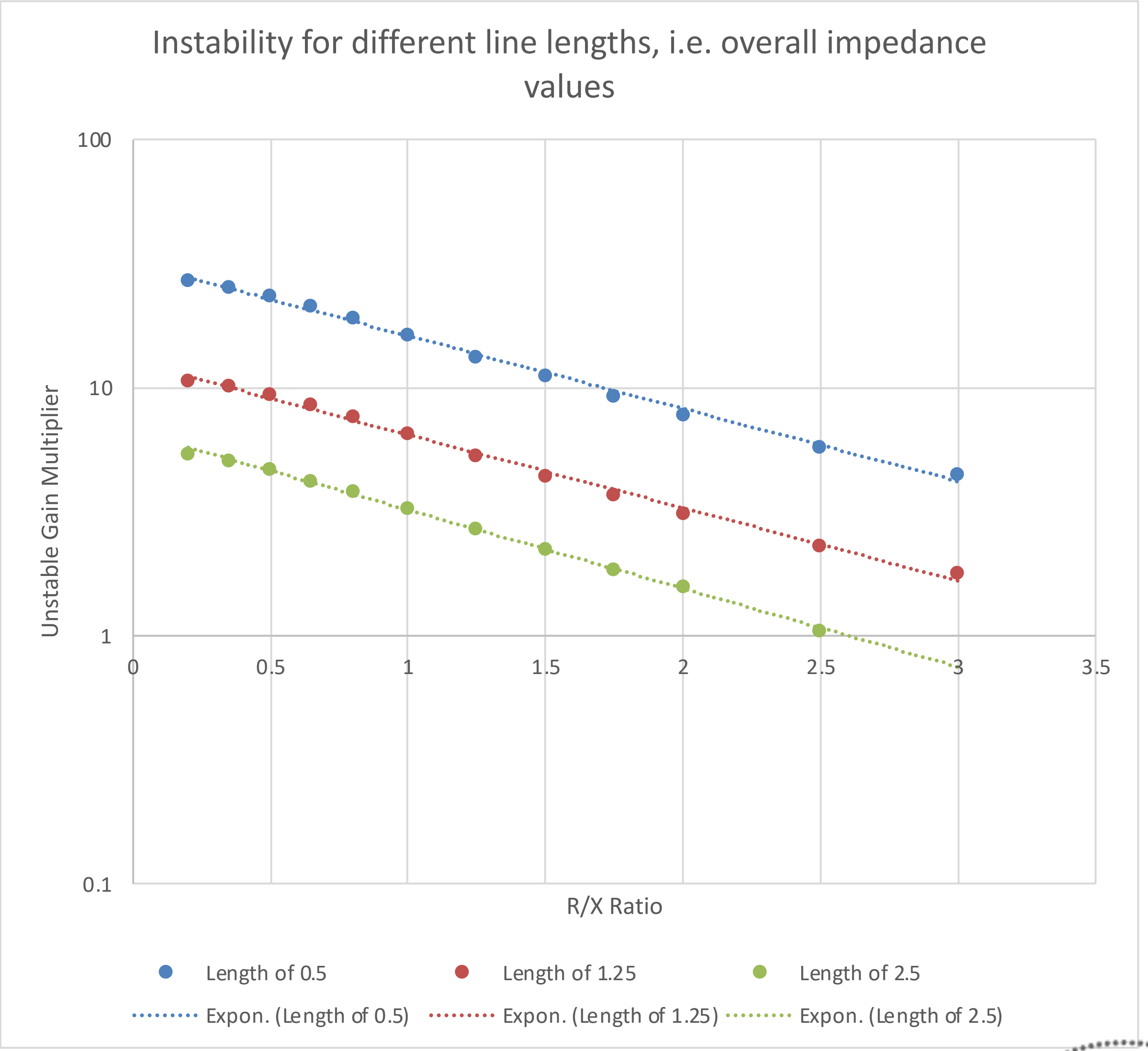
Disturbance Cancellation Loop:

- The network model treats all of the other load and generation on the network as an exogenous disturbance.
- The Disturbance Cancellation Loop estimates and counteracts the exogenous disturbance in real-time, and subtracts it from the input.



Effect of R/X Ratio

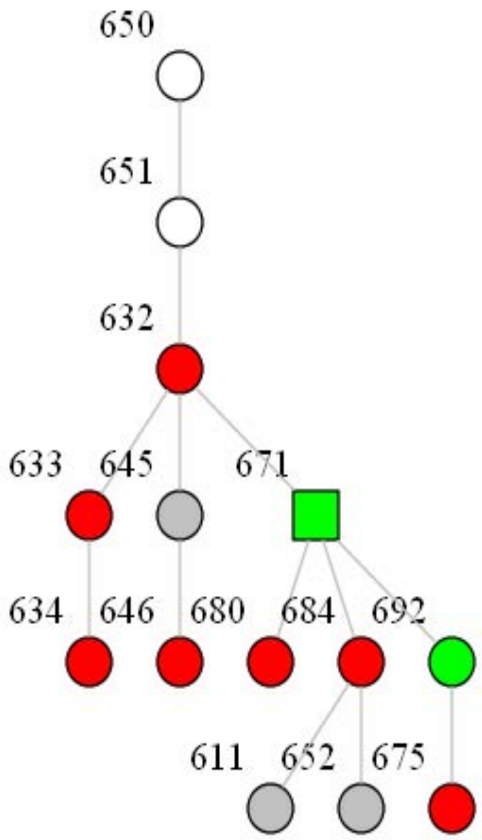
- The PI controller assumes that variable pairs P-δ and Q-V are reasonably well decoupled. This assumption holds for networks with small R/X ratios.
- Non-negligible R/X can cause controller instabilities. These instabilities can be addressed by reducing the PI gain.
- Because the MIMO LQR feedback is designed with a network model, it can work with arbitrary R/X ratios.



PI Controller Feasibility Tool

This tool allows a user to sequentially place actuator-performance node pairs to understand how each additional placement informs feasible locations for the next placement.

Sample result:
With actuators at 645, 611, and 652 (gray), the green and red colors indicate good/bad places to place an actuator that will track the phasor at node 671. Placing the actuator at node 671 or 692 (green) ensures tracking of all performance nodes



J. Swartz, B. Wais, E. Ratnam and A von Meier, "Visual Tool for Assessing Stability of DER Configurations on Three-Phase Radial Networks." Submitted to IEEE Powertech 2021. arXiv preprint available at arXiv:2011.07232