Distribution Synchrophasors for Control Applications

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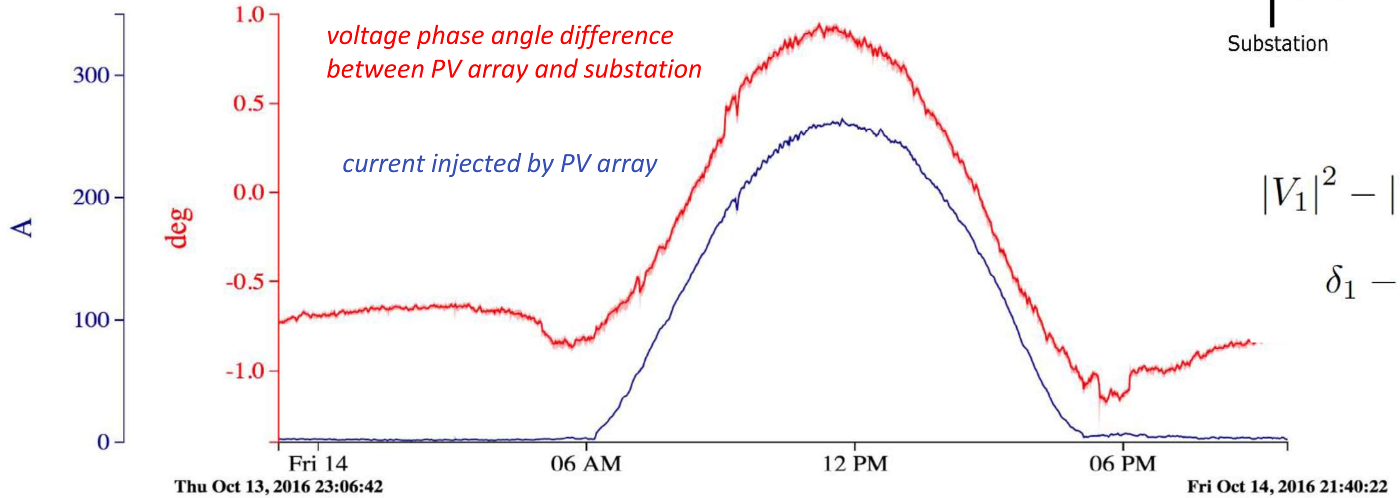
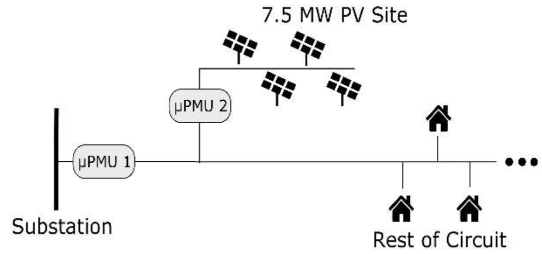
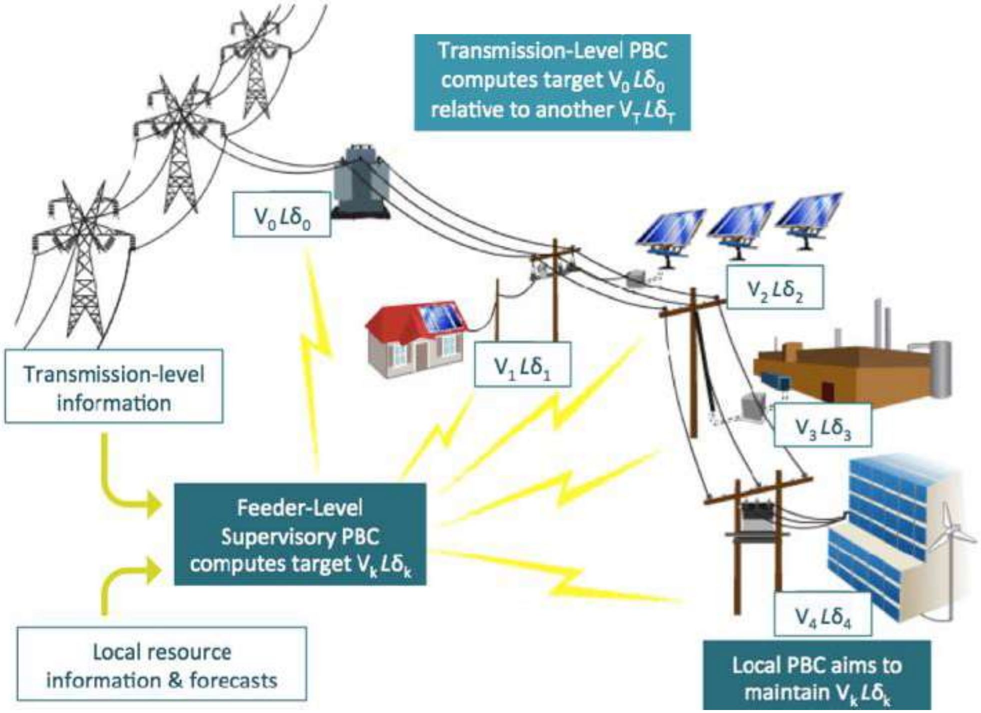
High-precision µPMU measurements reveal power flows even at the distribution level





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

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



Phasor-Based Control

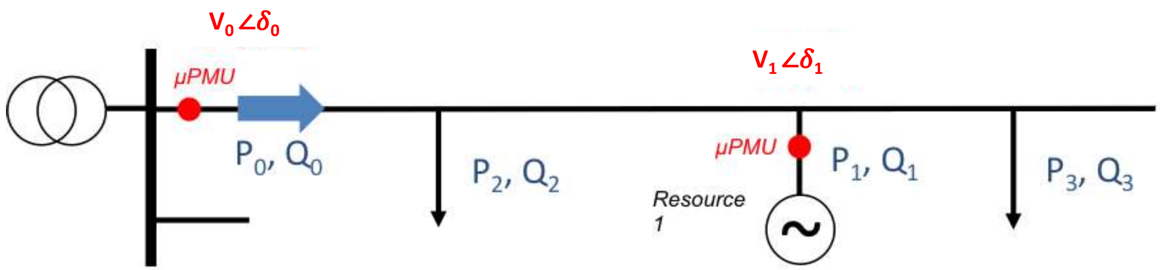
In PBC, resources act to maintain a target voltage phasor (magnitude and angle) difference between a pair of locations.

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

Motivating Intuition for Phasor-Based Control



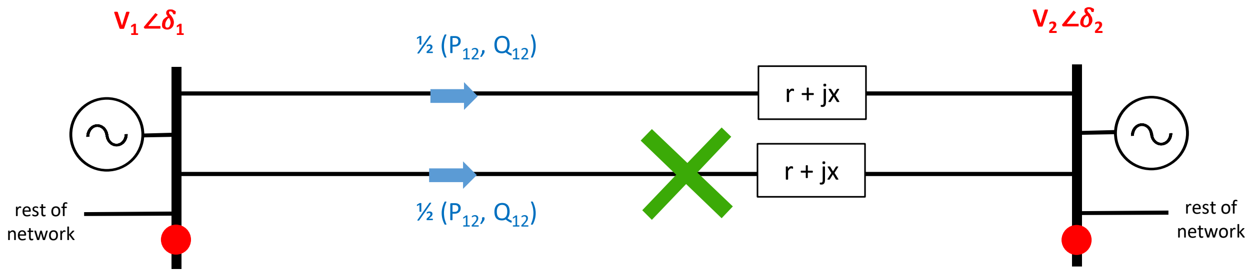
What should Resource 1 be doing?

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

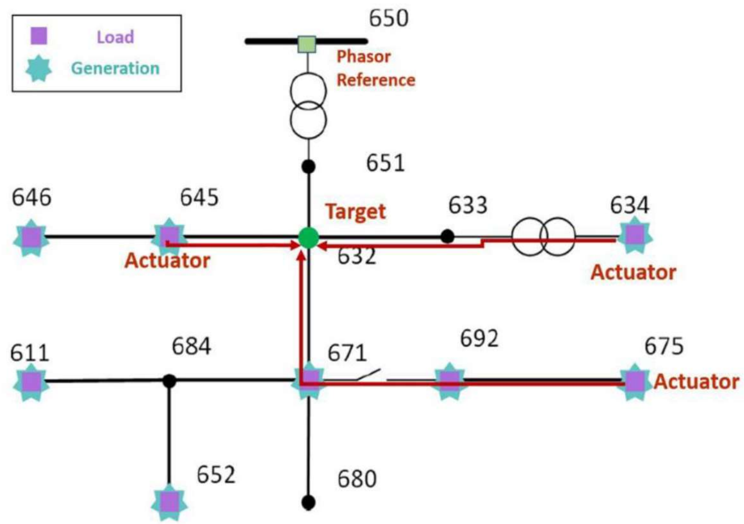
Supervisory controller performs a power flow optimization, whose results it expresses in terms of target phasors at performance nodes

- *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

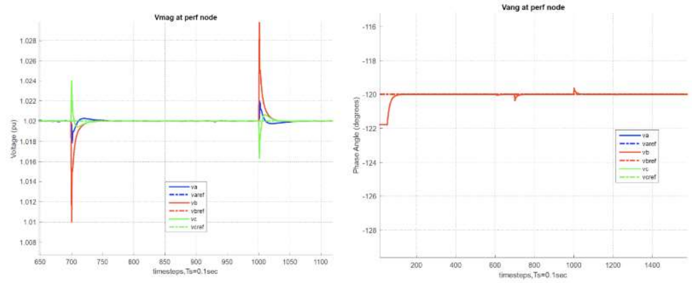
Test cases studied:

- *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*

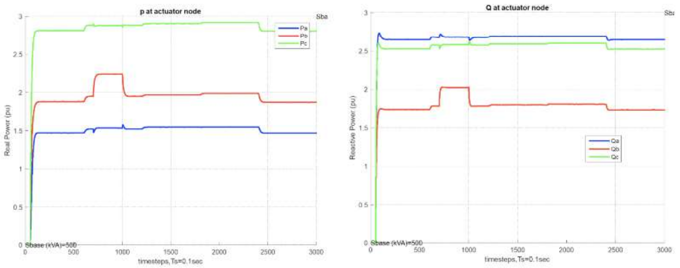


J. Swartz, T.G. Roberts, A. von Meier and E. Ratnam, "Local Phasor-Based Control of DER Inverters for Voltage Regulation on Distribution Feeders." *IEEE GreenTech Conference*, Oklahoma City, OK, April 2020.

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*

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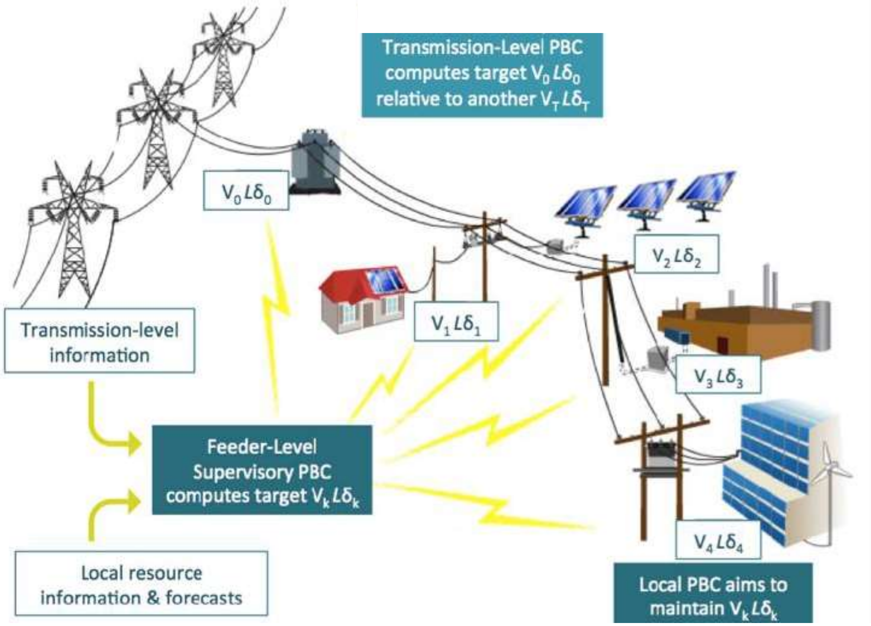

Conclusion

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 distribution utility manage power flows and volatility on the grid

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

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 (accepted).
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)