Micro-Synchrophasors for Distribution Systems

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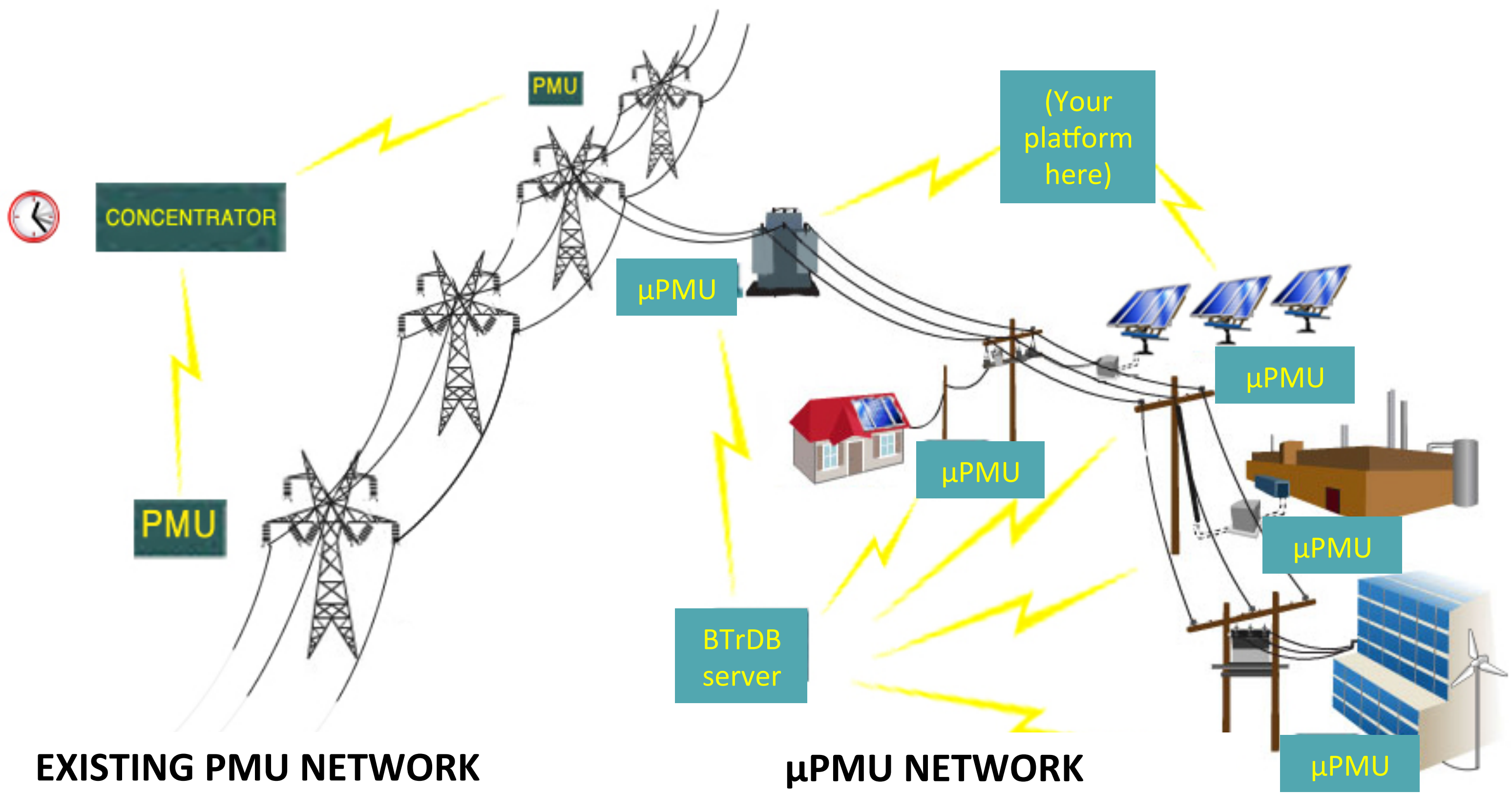
Micro-synchrophasor network concept:

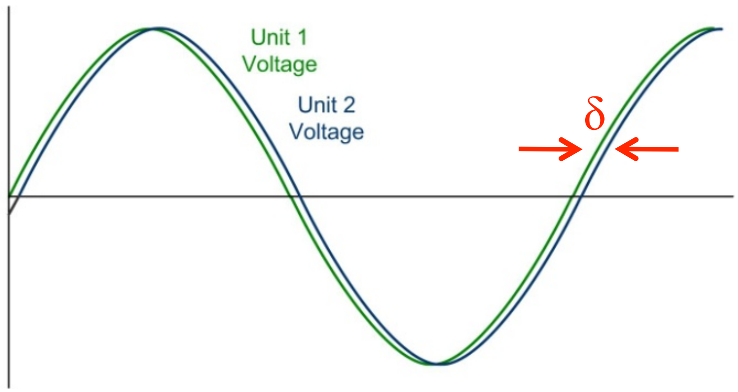
Create visibility for distribution circuits behind the substation to support active management and integration of distributed resources



EXISTING PMU NETWORK
Transmission System

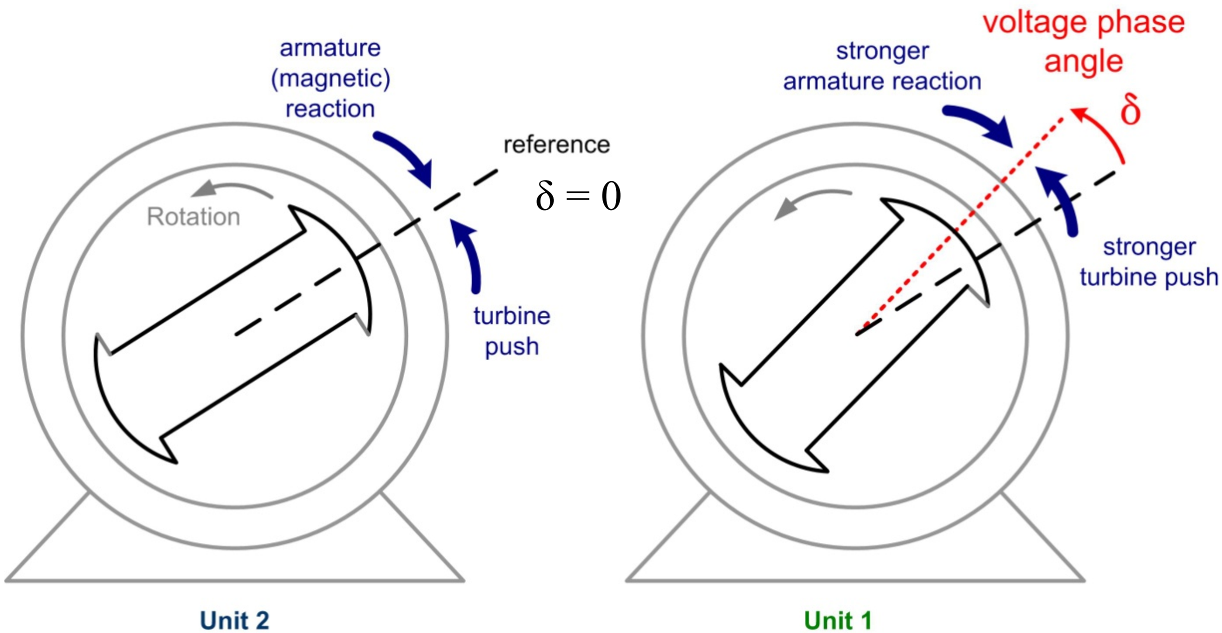
µPMU NETWORK
Distribution System

Synchrophasors compare voltage phase angle at different locations



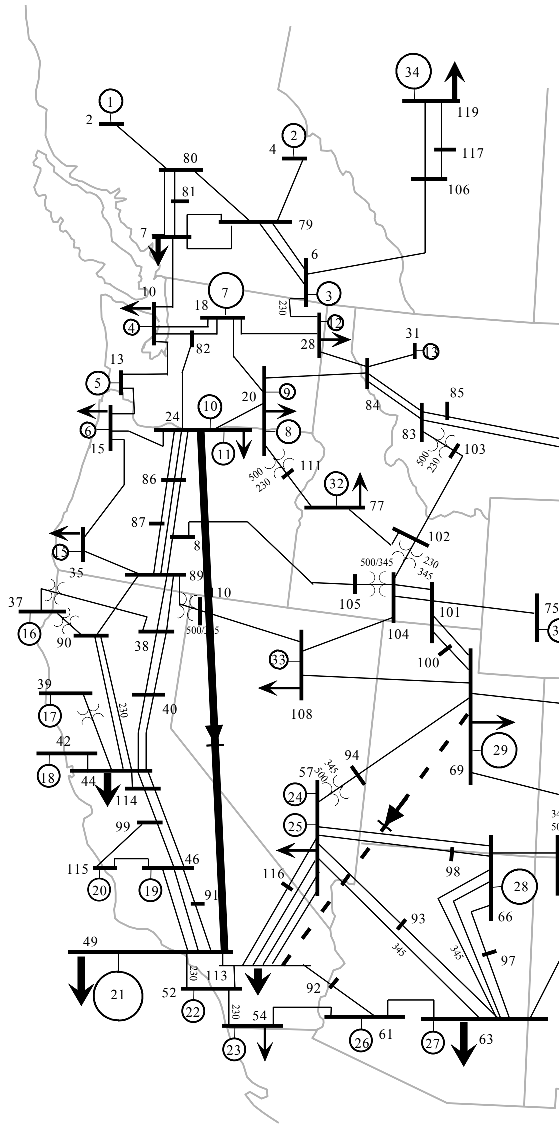
The small phase angle δ between different locations on the grid drives a.c. power flow

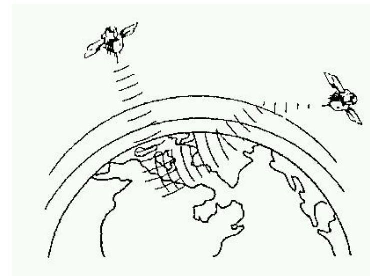
$$P \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$



Power injection to the grid is greater where voltage phase angle is farther advanced. Power flows from Unit 1 toward Unit 2.

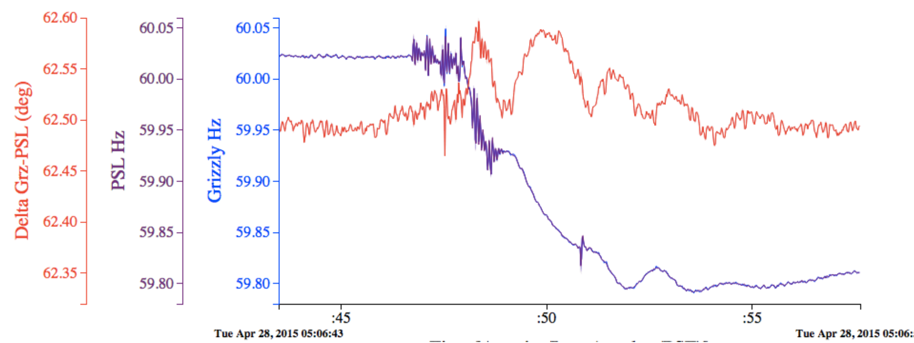
Synchrophasors compare voltage phase angle at different locations by cross-referencing *simultaneous* measurements, using same clock



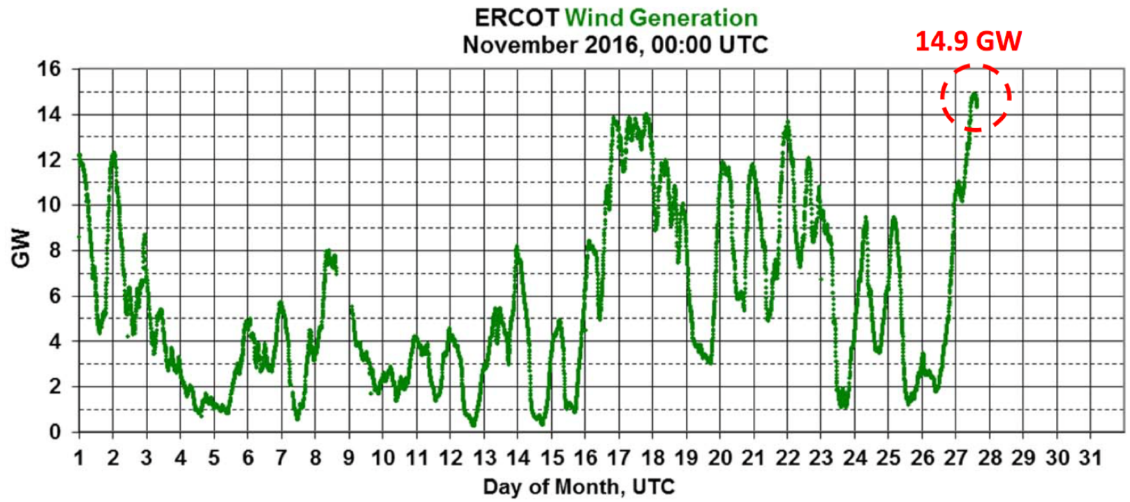


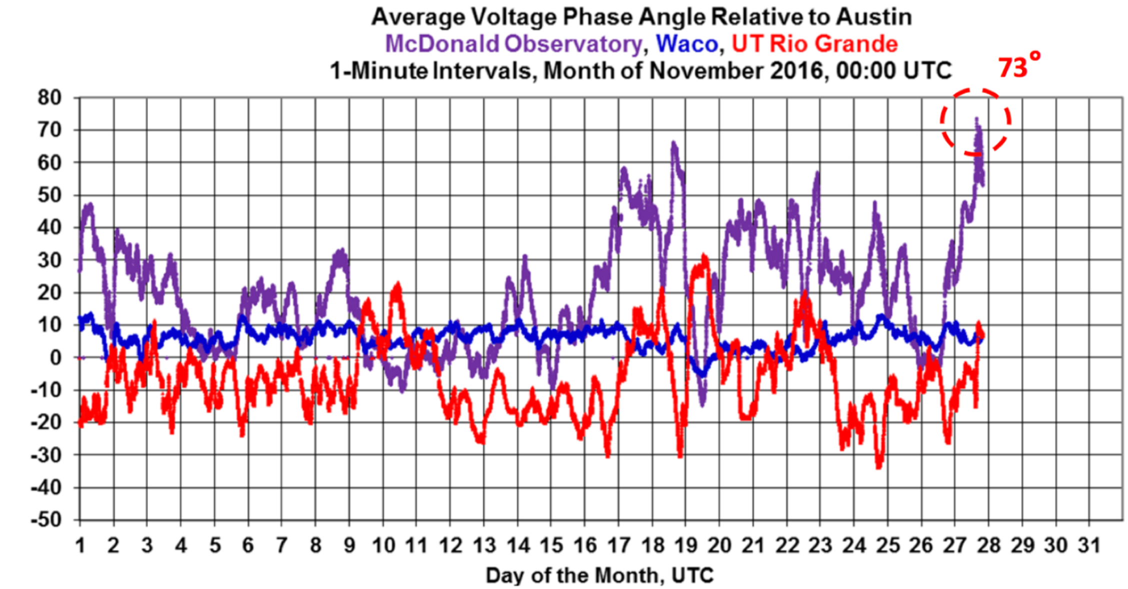
GPS time stamp

Phasor Measurement Units (PMUs)



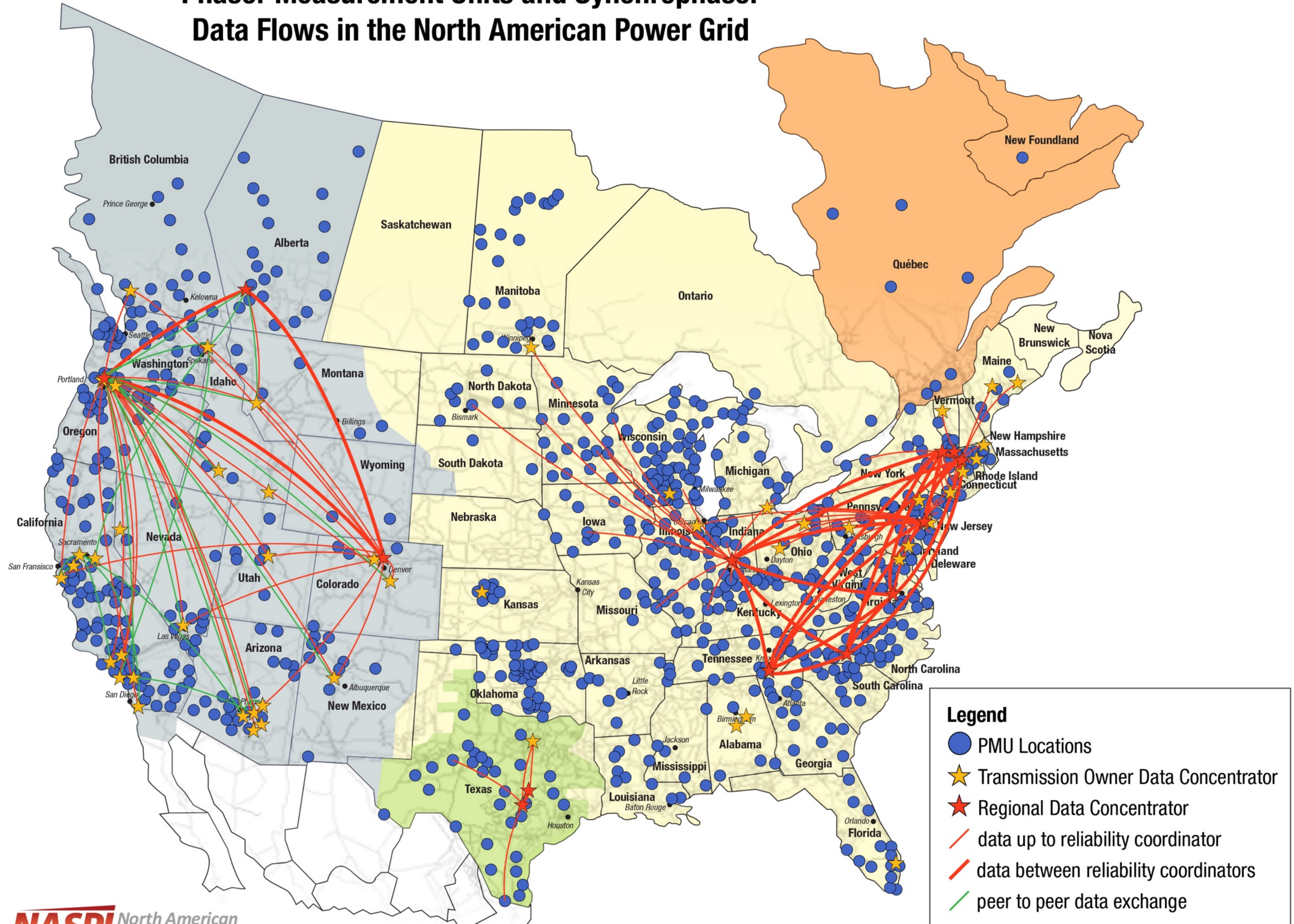
Synchronous data





Texas Synchrophasor Network   Mack Grady, Baylor University

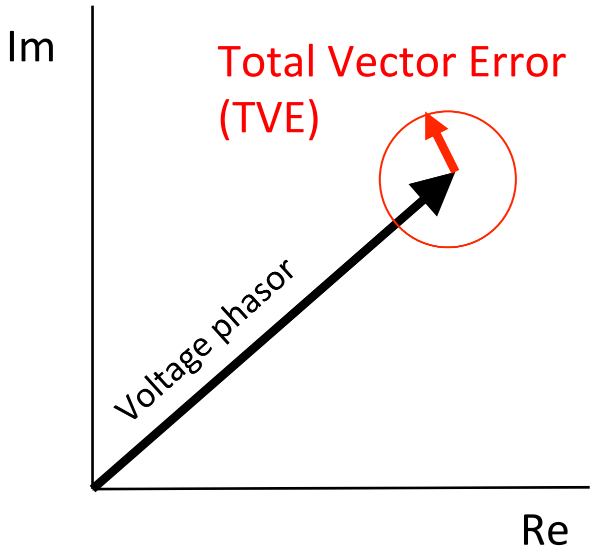
Phasor Measurement Units and Synchrophasor Data Flows in the North American Power Grid



With information available as of March 9, 2015

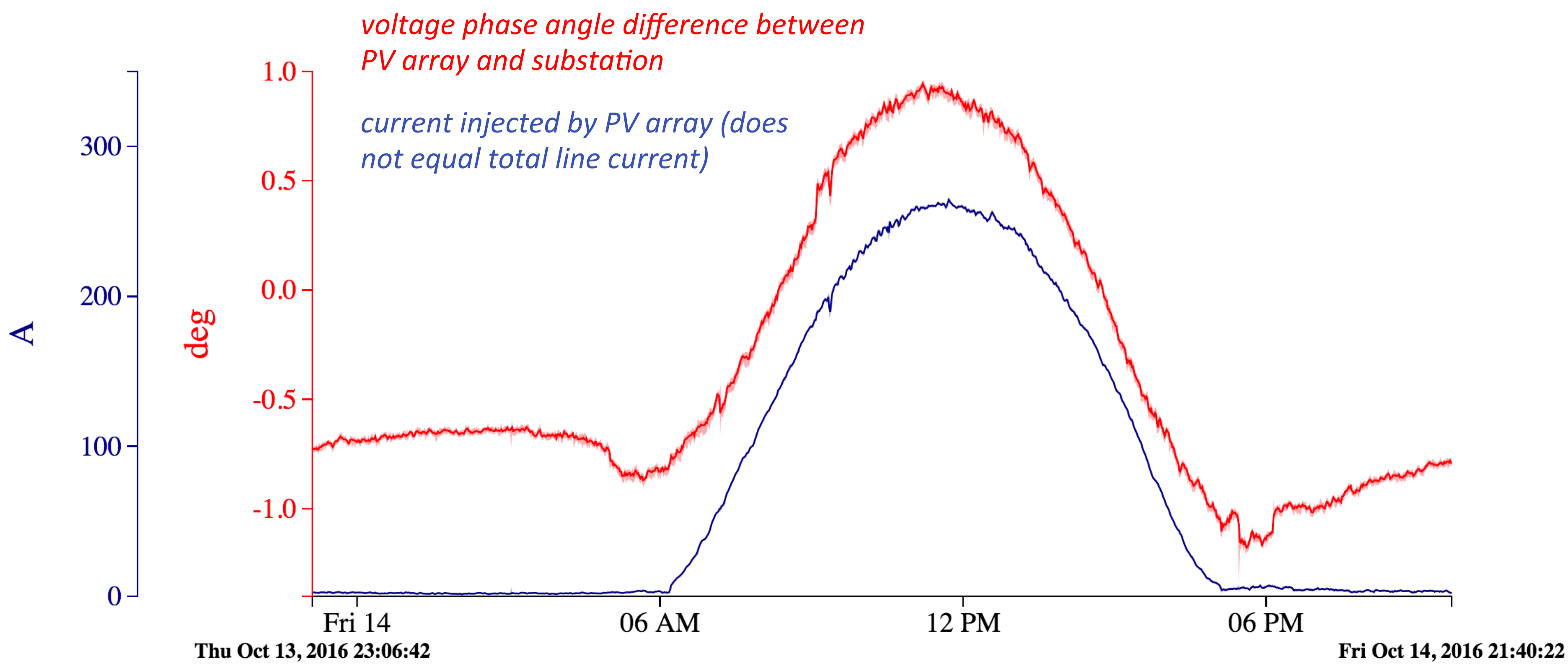
Why PMUs mostly on transmission, not distribution systems to date?

- Historically, no need (but this is changing):
  - unidirectional power flow, from substation to load
  - unquestioned stability of distribution system
- Cost / value proposition
- More challenging measurements: fractions of a degree



Transmission PMU performance
***~ 1% TVE** is not precise enough*
for distribution:
error of $\sin^{-1} 0.01 \approx 0.6^{o}$
is greater than signal

Illustration: Measured phase shift along 12kV distribution circuit



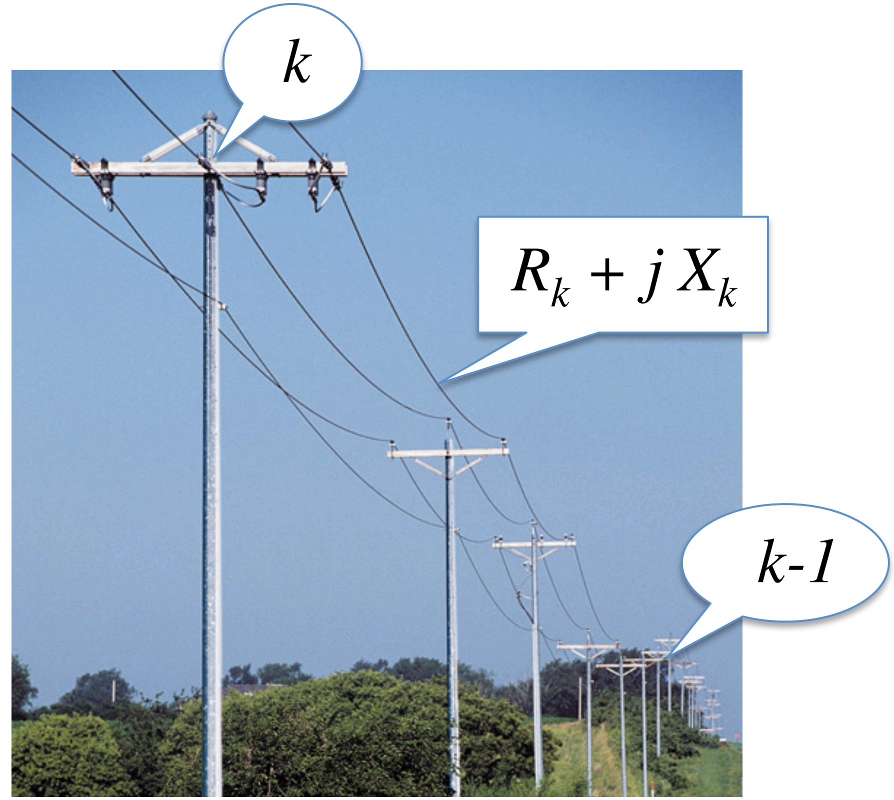
Signal of interest is on the order of 0.01 - 0.1^o
too small for typical transmission PMUs to resolve detailed power flow behind the substation

at 60 Hz 1 cycle ≈ 0.016 sec
0.1^o ≈ 4.6 μs

Distribution systems are tricky…

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

this nice approximation doesn't work



$$|V_{k-1}|^2 - |V_k|^2 \approx 2(R_k P_k + X_k Q_k)$$

$$\delta_{k-1} - \delta_k \approx \frac{X_k P_k - R_k Q_k}{|V_k||V_{k-1}|}$$

both X and R show up in these expressions; P and Q are not decoupled like in transmission

…and this doesn't even include three-phase imbalance!

Linear approximations derived from DistFlow equations for radial feeders by Dan Arnold, Roel Dobbe and Michael Sankur, UCB

Challenges for distribution synchrophasors as compared to transmission:

- smaller voltage angle differences
- more noise in measurements

  → very small signal-to-noise ratio
- different X/R ratios (inductance/resistance of distribution lines)

  → common approximations relating voltage phasors to impedances and power flows are not okay
- unbalanced three-phase systems
- distribution network models tend to have poor fidelity
- few measuring points compared to network nodes
- lack of access and tools to integrate with other data, e.g. smart meters

  → hard to do a full "state estimation"

Distribution Synchrophasor Applications

Event identification: use µPMU measurements to detect and explain disturbance events. Relies on precision time stamps and high-resolution time-series measurements, more than on accurate absolute or comparative multi-location measurements at a single point in time:

- ***Automatic event detection and notification***. Scan µPMU database and issue notifications when anomalies occur, e.g. voltage sags; many options for defining thresholds.
- ***Event classification.*** Categorize events, e.g. distinguish locally-caused vs. transmission-level voltage sags by comparing synchronized measurements from different locations.
- ***High impedance fault detection***. Distinguish between faults and load changes, e.g. arc flashes and motor starts, by comparing synchronized measurements from different locations.
- ***Statistical event characterization and learning***. Analysis based on large numbers of rapid queries, made possible by logarithmic search process.

Distribution Synchrophasor Applications

Distribution State Estimation: use µPMU measurements in conjunction with other available data (SCADA, AMI) to estimate the state variables (voltage phasors) throughout an entire distribution network, including unmonitored nodes.

Topology detection: use µPMU measurements to assess the connectivity or topology (open/closed state of switches) of a distribution network.

Fault Location: use µPMU measurements to precisely locate faults. Requires validated model with impedances; sensitive to number and placement of µPMUs, and hinges on PT/CT calibration.

Cyber-Security: use µPMU measurements to detect conditions that are inconsistent with system status as expected or reported elsewhere, to reveal tampering with data or physical equipment.

Distribution Synchrophasor Applications

Model validation: use ultra-precise μPMU measurements to confirm, deny, or correct existing models of real-world distribution networks.

- ***Phase (ABC) connectivity identification.*** Relatively straightforward; main challenge is accounting for multiple delta-wye transformers between measurement points absent reliable model data.
- ***Line segment impedance calculation.*** Based on measured current and voltage phasors at each end of the segment. Trivial in principle ($V = IZ$) yet challenging in practice due to three-phase asymmetry and PT/CT errors that are large compared to changes along a line segment.
- ***Device models.*** Understand dynamic behaviors of inverters and machines, including unintended interactions and possible control instabilities.

Distribution Synchrophasor Applications

Distributed Generation (DG) and Load Characterization:

use µPMUs to measure and understand time variation among DG and loads, and how DG affects distribution networks:

- ***Disaggregate DG from load, behind net meter***
- ***Detect reverse power flow.*** Phase angle reveals direction of current. Note that current does not cross zero when real power flow reverses, due to the presence of reactive power.
- ***Load Characterization***. Assess load volatility and voltage dependence with high-resolution measurements and correlations.
- ***Assess DER impacts on feeder voltage magnitude and volatility.*** Opportunity to apply statistical methods.
- ***DG feeder hosting capacity estimation.*** Support planning studies through model validation to better predict DG impacts.

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Distribution Synchrophasor Applications

Phasor-Based Control: use μPMU measurements to determine desired P and Q injections or consumption by controllable devices.

Control objectives may include, for example:

- ***voltage profile management***
- ***loss minimization***
- ***ancillary services coordination***
- ***balancing generation and load on a microgrid***
- ***microgrid islanding decisions based on grid behavior***
- ***assisted network reconfiguration by phasor matching across switch***

Micro-synchrophasors for Distribution Systems

Three-year, $4.4 M ARPA-E OPEN 2012 project (2013-2016) to

- develop a network of high-precision phasor measurement units (µPMUs) and high-speed database (BtrDB)
- explore applications of µPMU data for distribution systems to improve operations, increase reliability, and enable integration of renewables and other distributed resources
- evaluate the requirements for µPMU data to support specific diagnostic and control applications

Micro-synchrophasors for Distribution Systems

18-month, $2M Plus-Up extension project 2017-2018

Collaboration with three commercialization partners with different application foci:

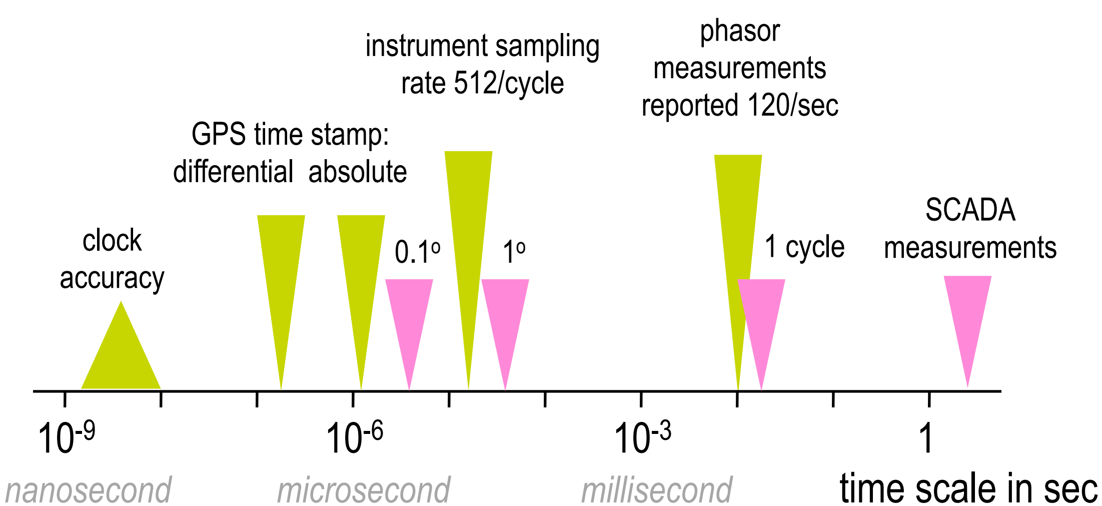
Smarter Grid Solutions: Planning, diagnostics & mitigation for high-penetration PV distribution

Doosan Grid Tech (formerly 1EnergySystems): Information infrastructure for distribution monitoring and control

PingThings: Stream analysis software for real-time grid data, T&D disturbance event detection and analysis

Power Standards Lab µPMU
(developed through ARPA-E)

- built on PQube3 power quality recorder
- capable of power quality mode with 512 samples per cycle
- time stamping to nanosecond precision, microsecond accuracy with GPS
- measures voltage & current, magnitude & angle (12 channels)
- 100V ~ 690V input
- 120 samples per second in PMU mode (each channel)
- local data buffering + batching (2 min), backup storage
- connectivity via Ethernet, 4G wireless



www.powerstandards.com

Sample utility polemount installation of µPMU
including GPS receiver, modem and antenna

PSL

ARPA-E µPMU Project

Field installations:

UC Berkeley/LBNL

Southern California Edison

Riverside Public Utilities

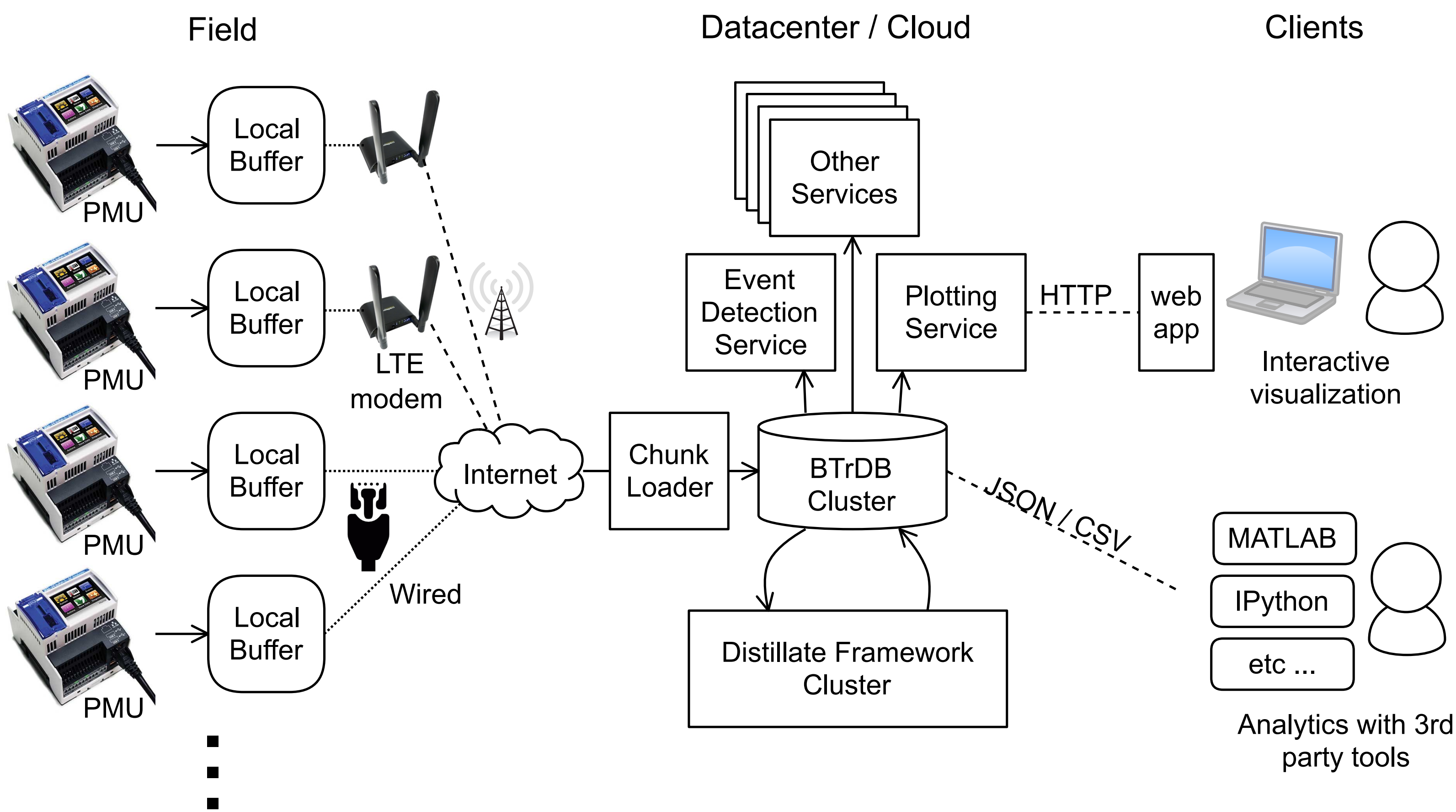
Alabama Power (Southern Co.)

Georgia Power (Southern Co.)

Tennessee Valley Authority

Pacific Gas & Electric Co.

Berkeley Tree Database (BTrDB)



ARPA-E research project configuration: 40+ µPMUs sending 120 Hz data via Ethernet or 3G/4G wireless, 12 streams per device (voltage and current magnitude & phase angle)

Michael Andersen, UC Berkeley

California Institute for Energy and Environment

Berkeley Tree Database (BTrDB) resolves the downsides of storing and utilizing large, high-resolution time-series data streams

- no need to compromise between data continuity, resolution, ease of access
- extremely fast searches (~200 ms for individual samples within months of 120-Hz data)
- performs online computation of data distillate streams (e.g. power, frequency, rates of change, differences between quantities)
- data available for viewing in plotter and downloadable through API for external analytic applications
- open source code available on github

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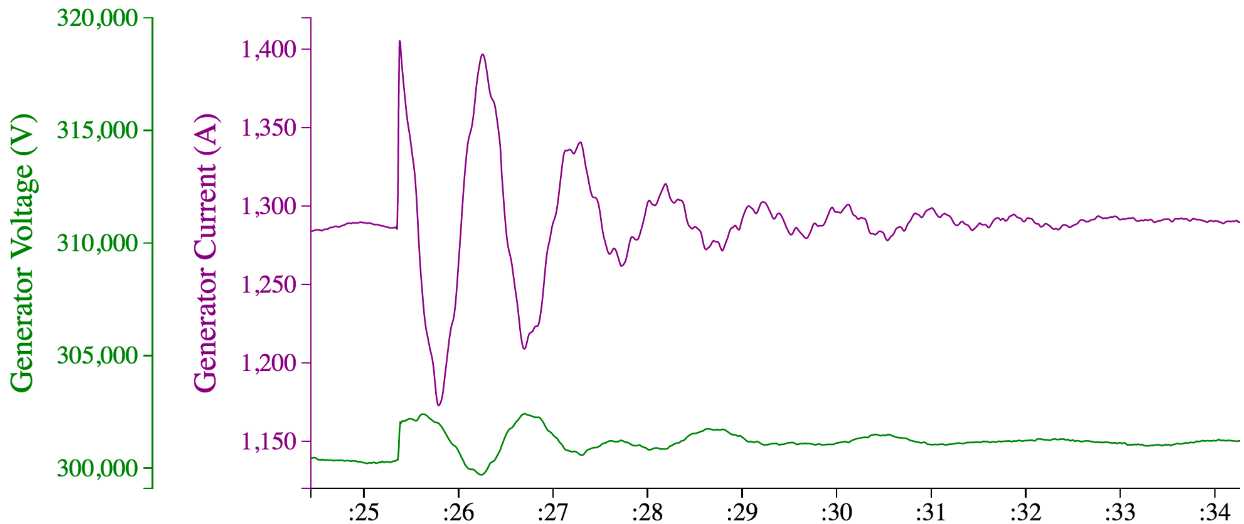
Use case: Mitigating system vulnerability to disturbances

PMU data reveal dynamic response across transmission and distribution:

- assess stability operating limits
- identify exposure to large disturbances, e.g. geomagnetic (GMD)
- diagnose local control issues, oscillations
- understand implications of reduced system inertia with inverter-based generation: the design basis has changed



time in seconds

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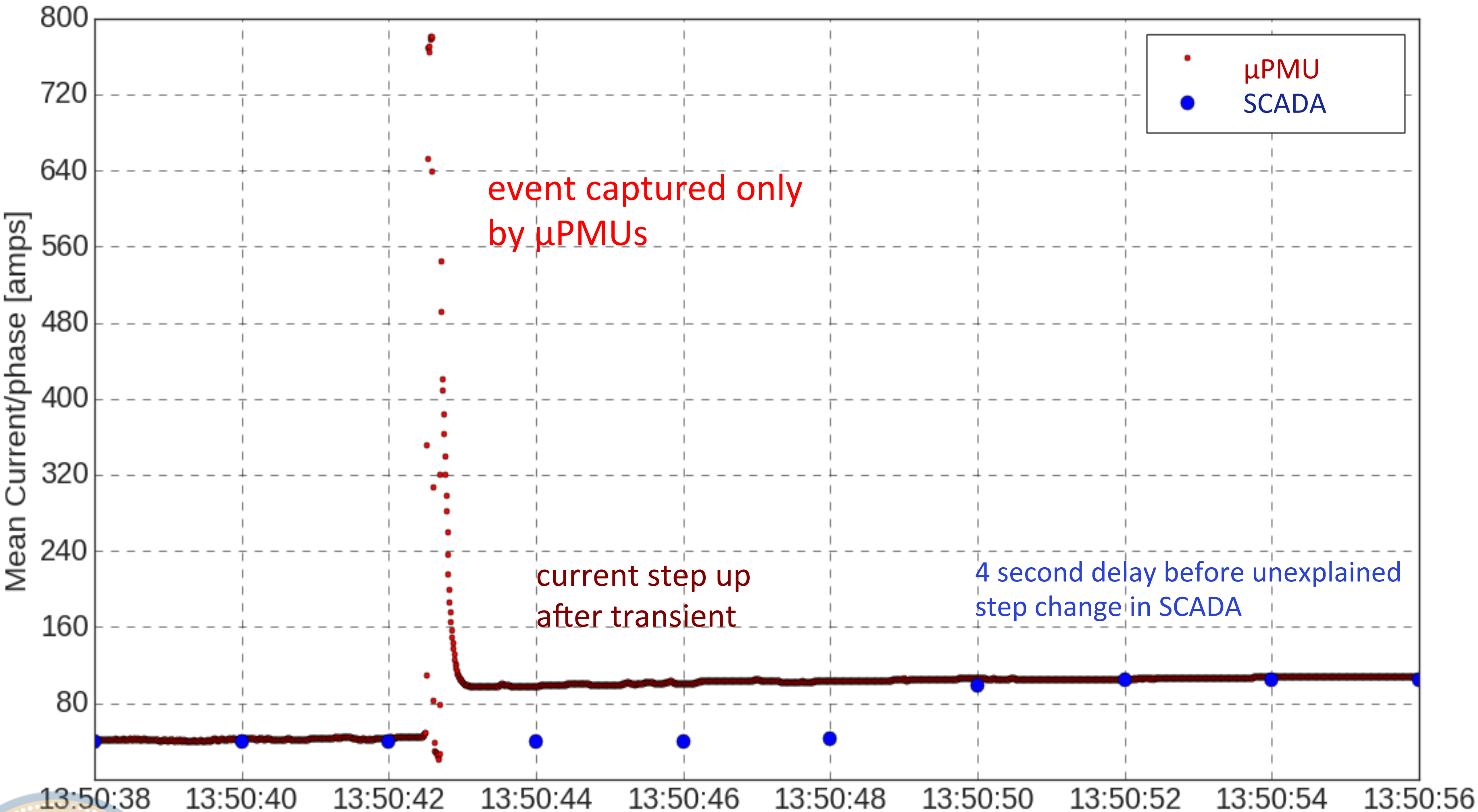
Use case: Transient event detection



Emma Stewart and Ciaran Roberts, Lawrence Berkeley National Lab

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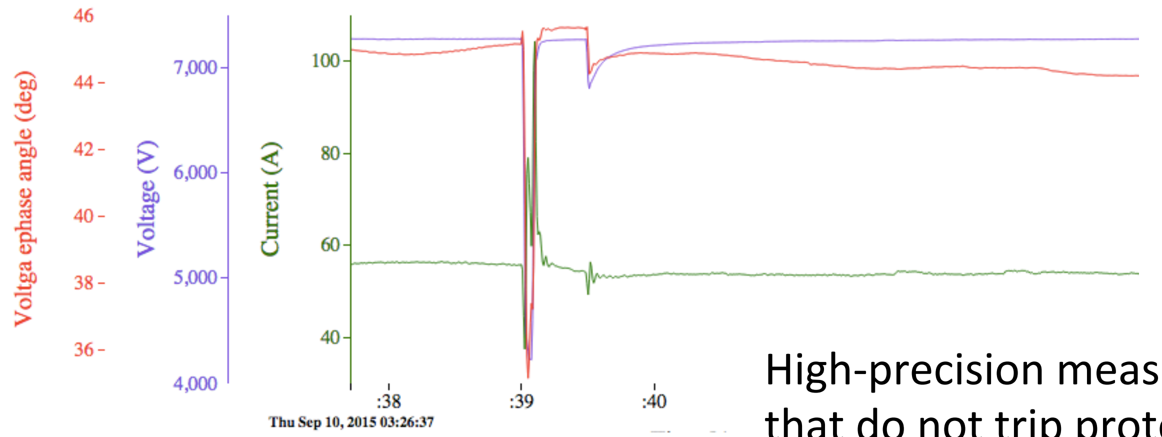
Use case: High-impedance fault detection



High-precision measurements capture events that do not trip protection, but may impact safety and power quality

Cross-referencing time-aligned data streams supports diagnostics to

- locate disturbance origin
- ascertain proper operation by distributed resources and protection coordination

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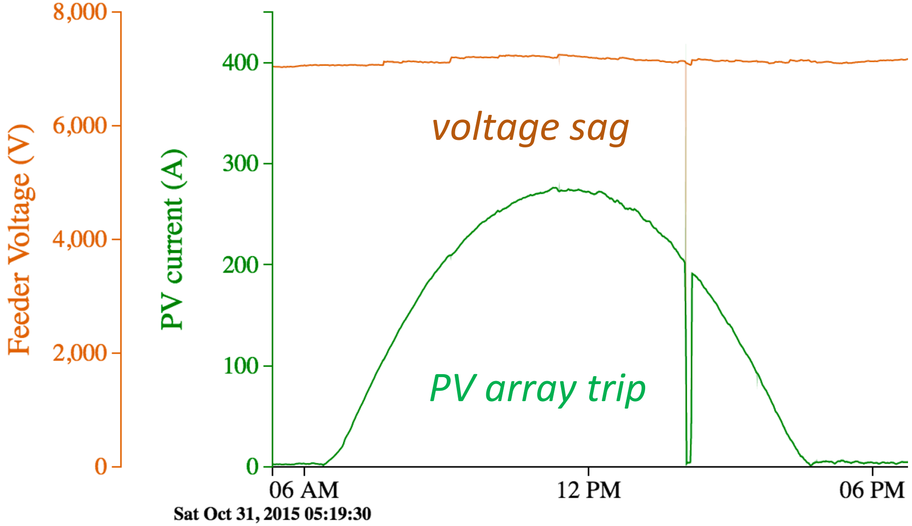
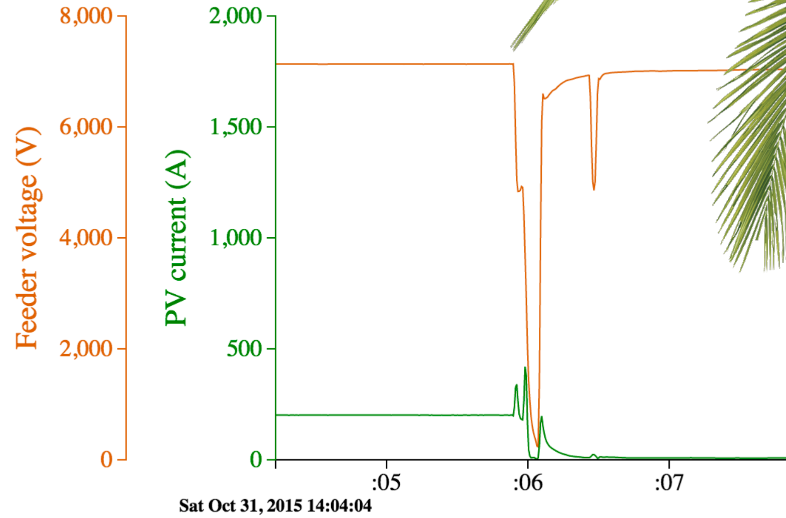
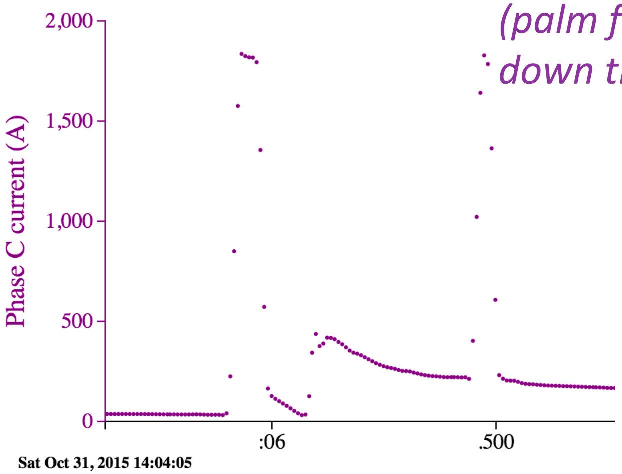
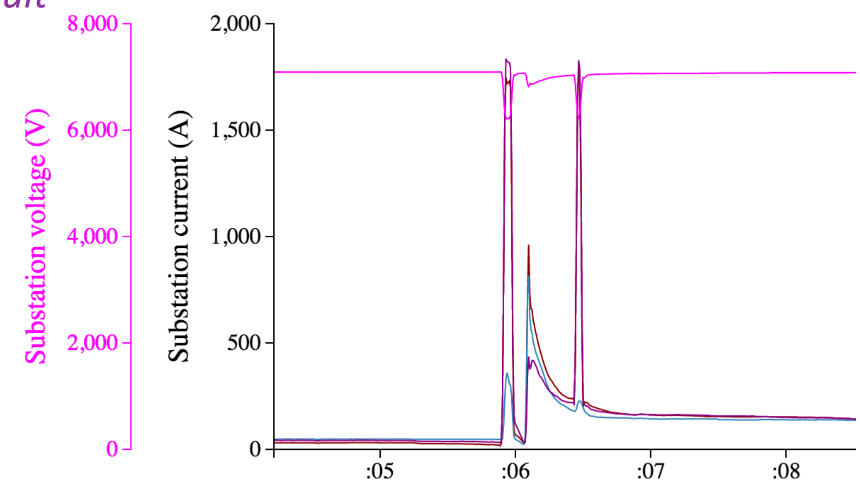
Use case: Diagnose cause of DG unit trips



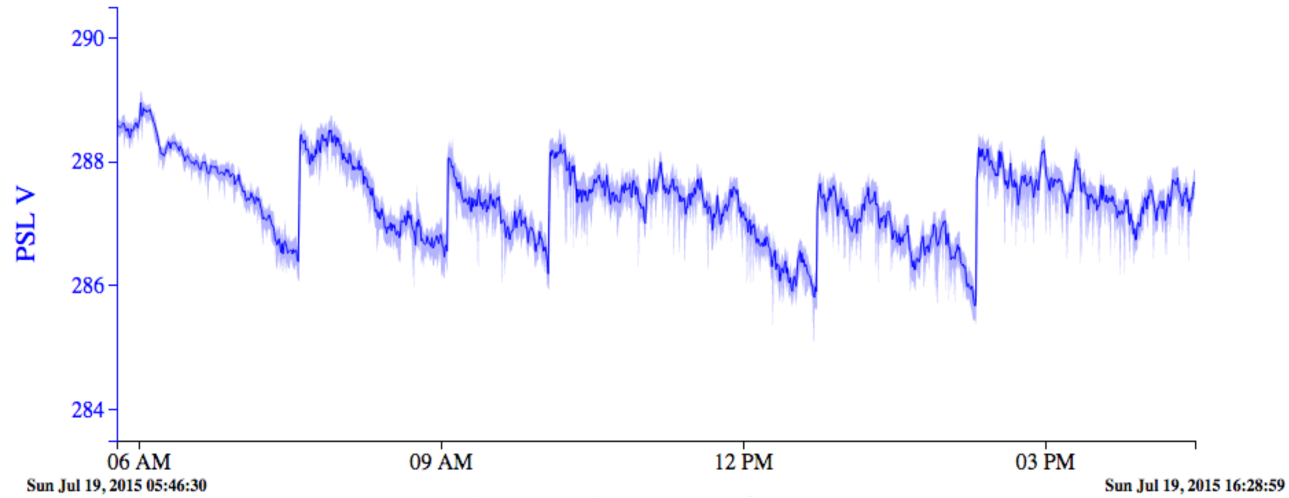


caused by phase B-C fault (palm frond contact) down the feeder

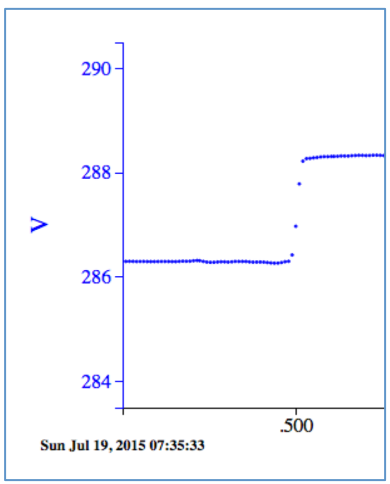




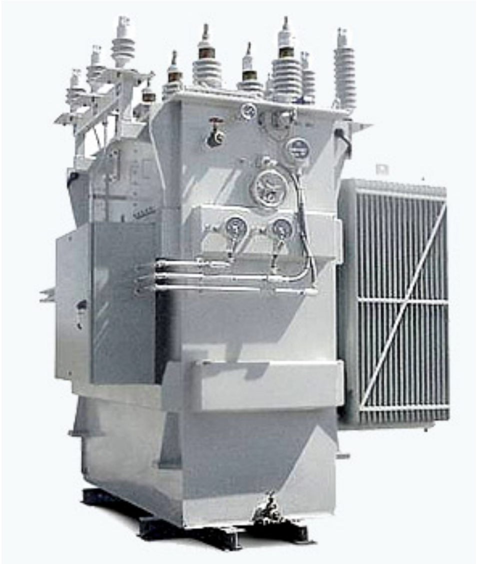
Use case: Detect normal and mis-operation of equipment



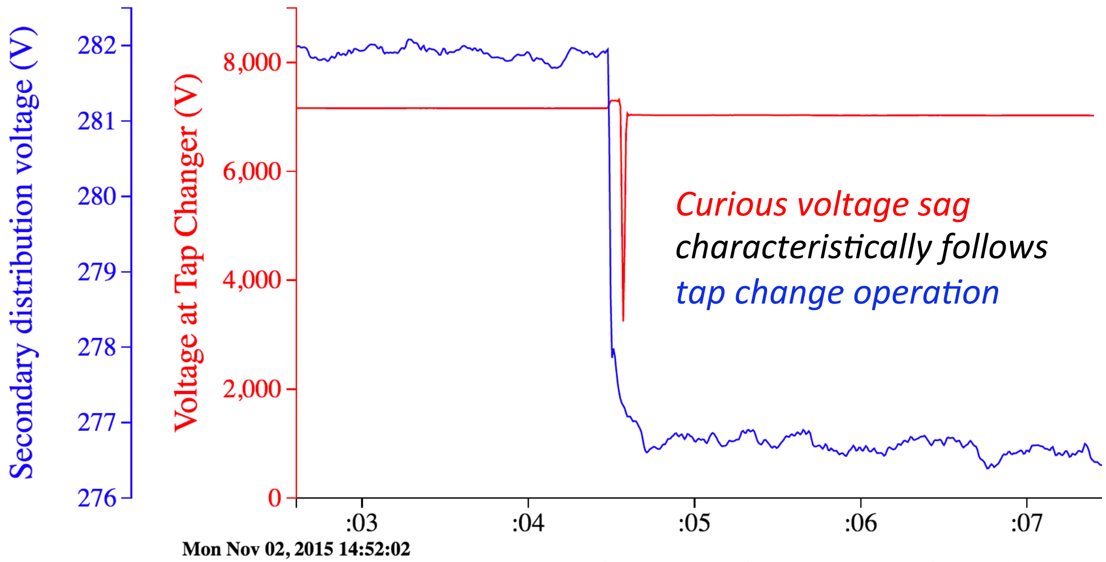
Tap changer at substation transformer steps voltage up and down as load changes over the course of the day

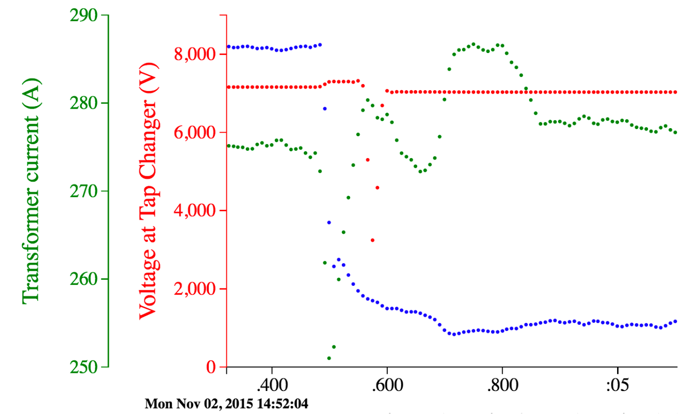


Tap change occurs over ~2 cycles Graph shows individual 120-Hz samples

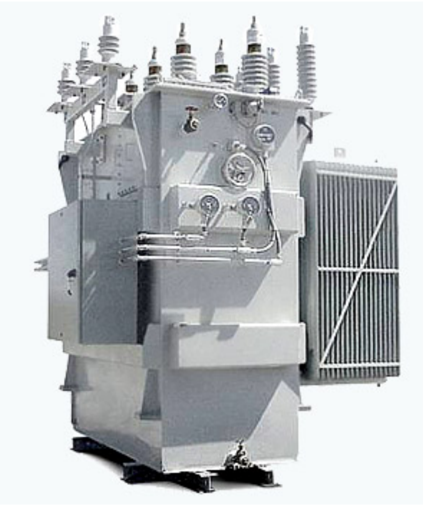


Use case: Detect normal and mis-operation of equipment





Example:
Anomaly in tap change signature gives early warning of transformer aging or incipient failure



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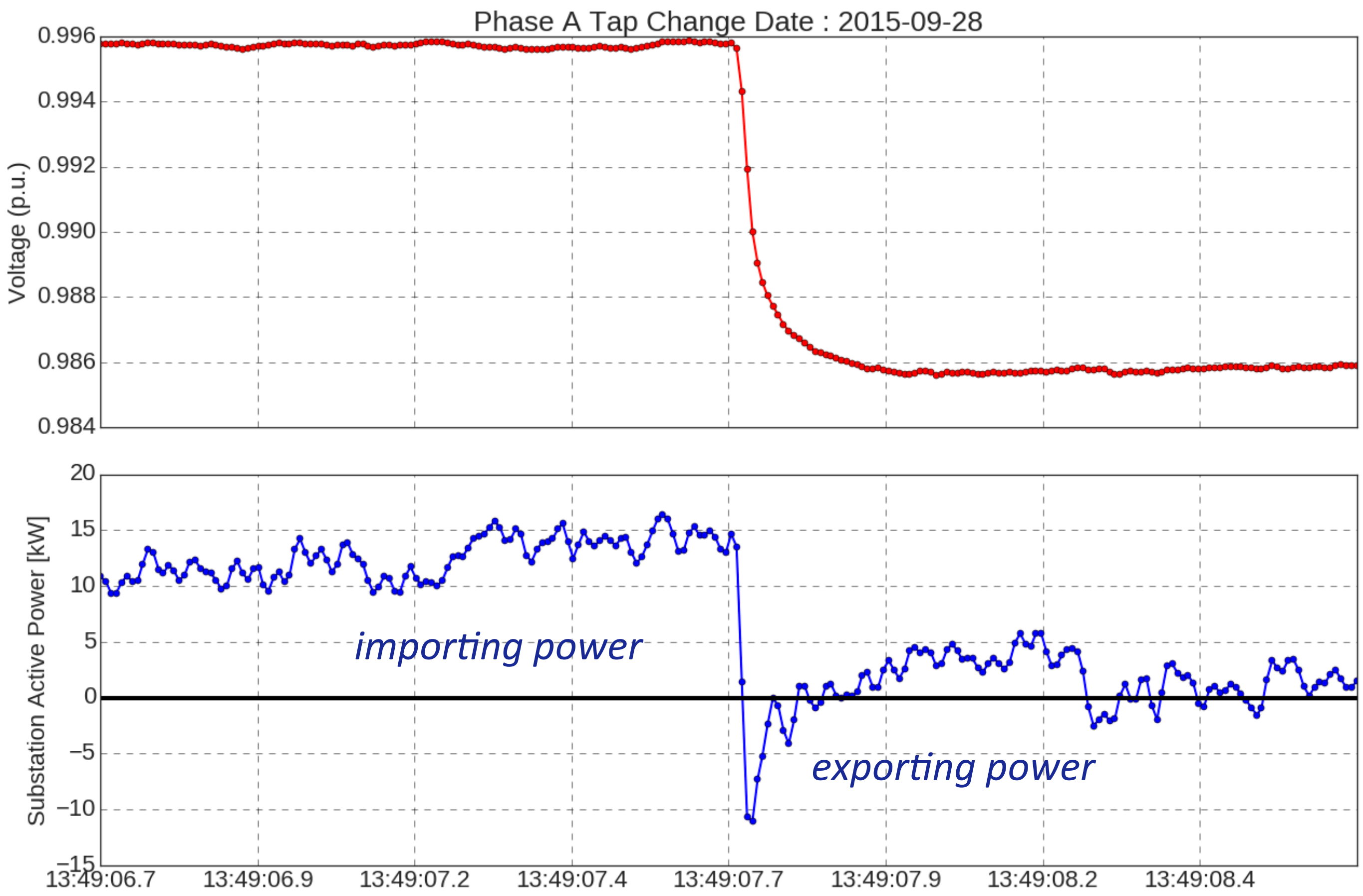
Use cases: Feeder and load model validation
Reverse power flow detection

Example: ascertain impacts of voltage regulation with hi-pen DG



1.2% step down in voltage

significant drop in kW due to highly voltage dependent load

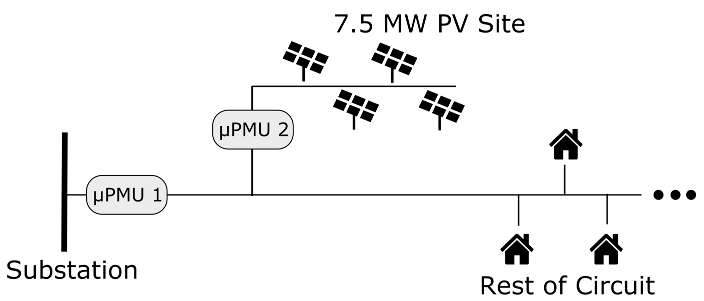
high-penetration solar PV feeder goes from net kW import to backfeed

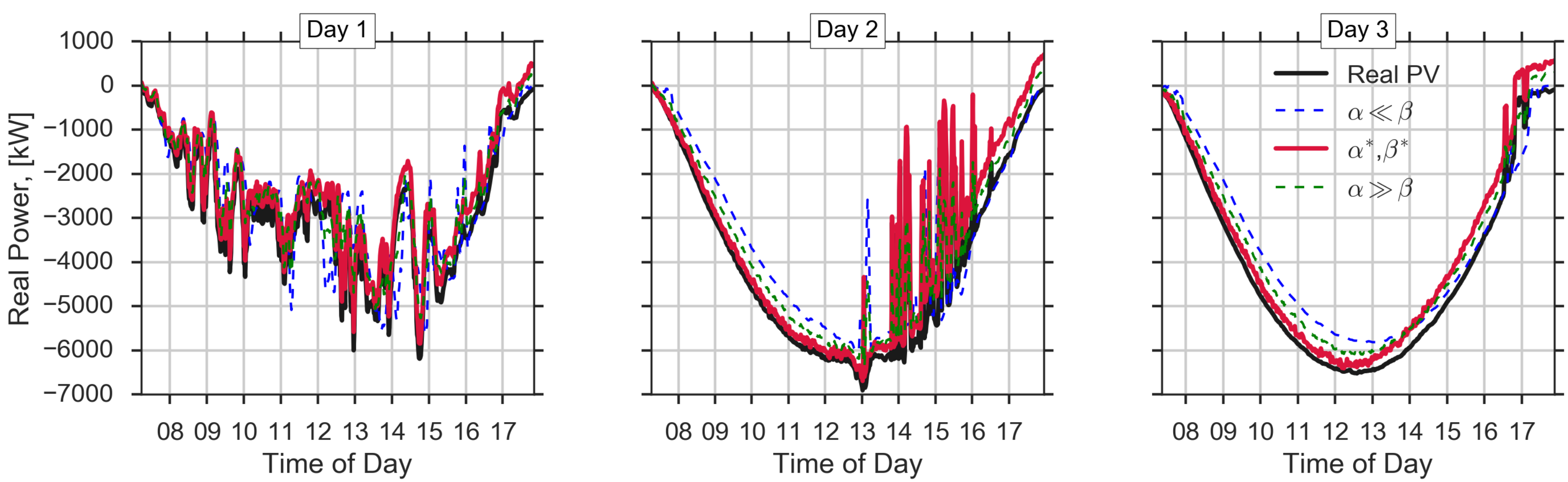
Ciaran Roberts and Emma Stewart, Lawrence Berkeley National Lab

Use case: Disaggregating net metered DG from load

Customer-owned solar generation can mask an unknown amount of load, creating vulnerabilities for the system (e.g. simultaneous DG trips, cold load pickup).

µPMU measurements on the utility side of the meter offer an alternative to telemetry on customer premises or 3rd party data, to create awareness for operators.





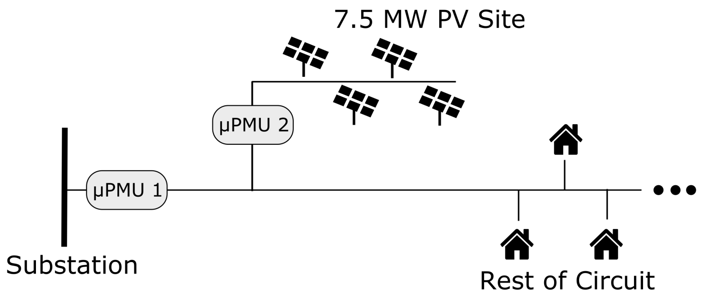
Ciaran Roberts and Emma Stewart, Lawrence Berkeley National Lab

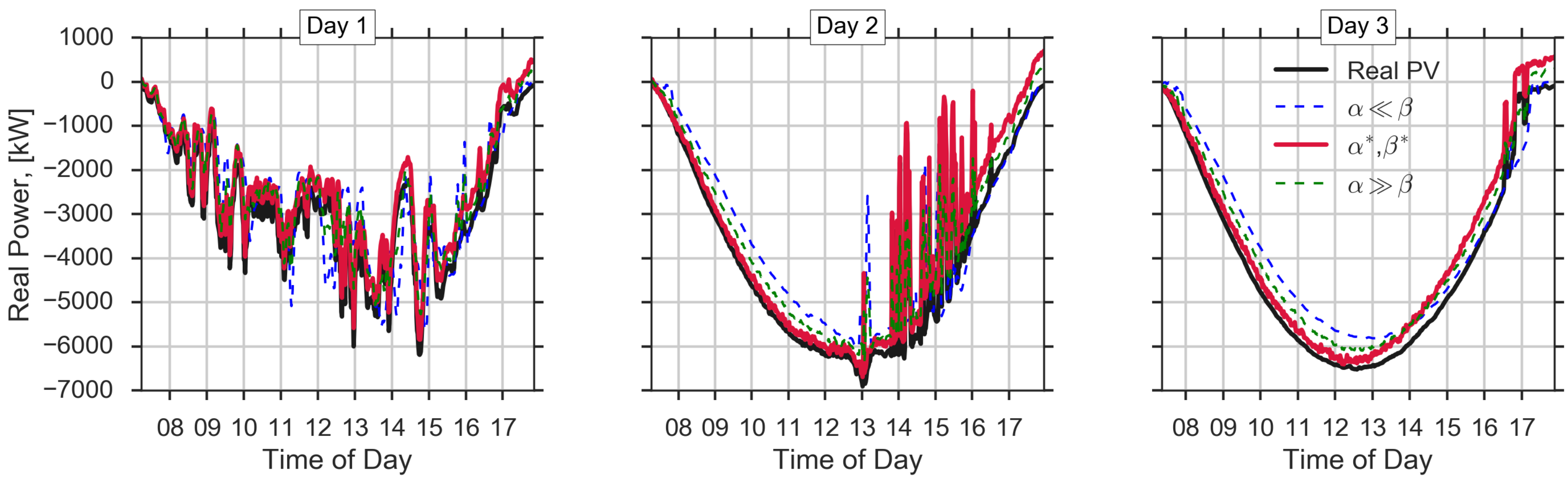
Use case: Disaggregating net metered DG from load

PV generation is estimated as a function of capacity, irradiance data and aggregate power measurement.

Model runs in real time to approximate actual performance of PV and identify masked load.

Test case: LBNL algorithm estimated actual PV generation (red) using only aggregate data from µPMU 1 and validated against direct PV measurement from µPMU 2 (black); performed within 6% RMSE over all sky conditions.





Ciaran Roberts and Emma Stewart, Lawrence Berkeley National Lab

Conclusions and Next Steps

- Distribution-specific synchrophasors and powerful data analysis toolkits are now becoming available
- A single monitoring network can create visibility and support diverse use cases on the distribution system
- Large potential exists to leverage PMU data for intelligence
- Important use cases for µPMU-based tools center on distributed resource integration
- Opportunities for collaboration include pilot projects with ARPA-E Plus-Up partners

Resources

Read the ARPA-E Project Impact Sheet at
http://beci.berkeley.edu/wp-content/uploads/2016/12/UCB-External-Project-Impact-Sheet_11102016.pdf

Peruse live and archival μPMU data at
http://plot.upmu.org and http://powerdata.lbl.gov/

Learn about μPMU hardware at
http://www.powersensorsltd.com/PQube3.php

Participate in the NASPI Distribution Task Team (DisTT)
www.naspi.org

Go straight to the source for BTrDB at
https://github.com/SoftwareDefinedBuildings/btrdb

Contact me with questions at vonmeier@berkeley.edu