Distribution Synchrophasors: Overview of Applications, Lessons Learned to Date and Opportunities for Future Research

Dr. Alexandra (Sascha) von Meier
Director, Electric Grid Research, California Institute for Energy and Environment
Adjunct Professor, Dept. of Electrical Engineering and Computer Science
University of California, Berkeley
vonmeier@berkeley.edu

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Micro-synchrophasors (µPMUs) for Distribution Systems

Three-year, $4.4 M ARPA-E project April 2013-2016

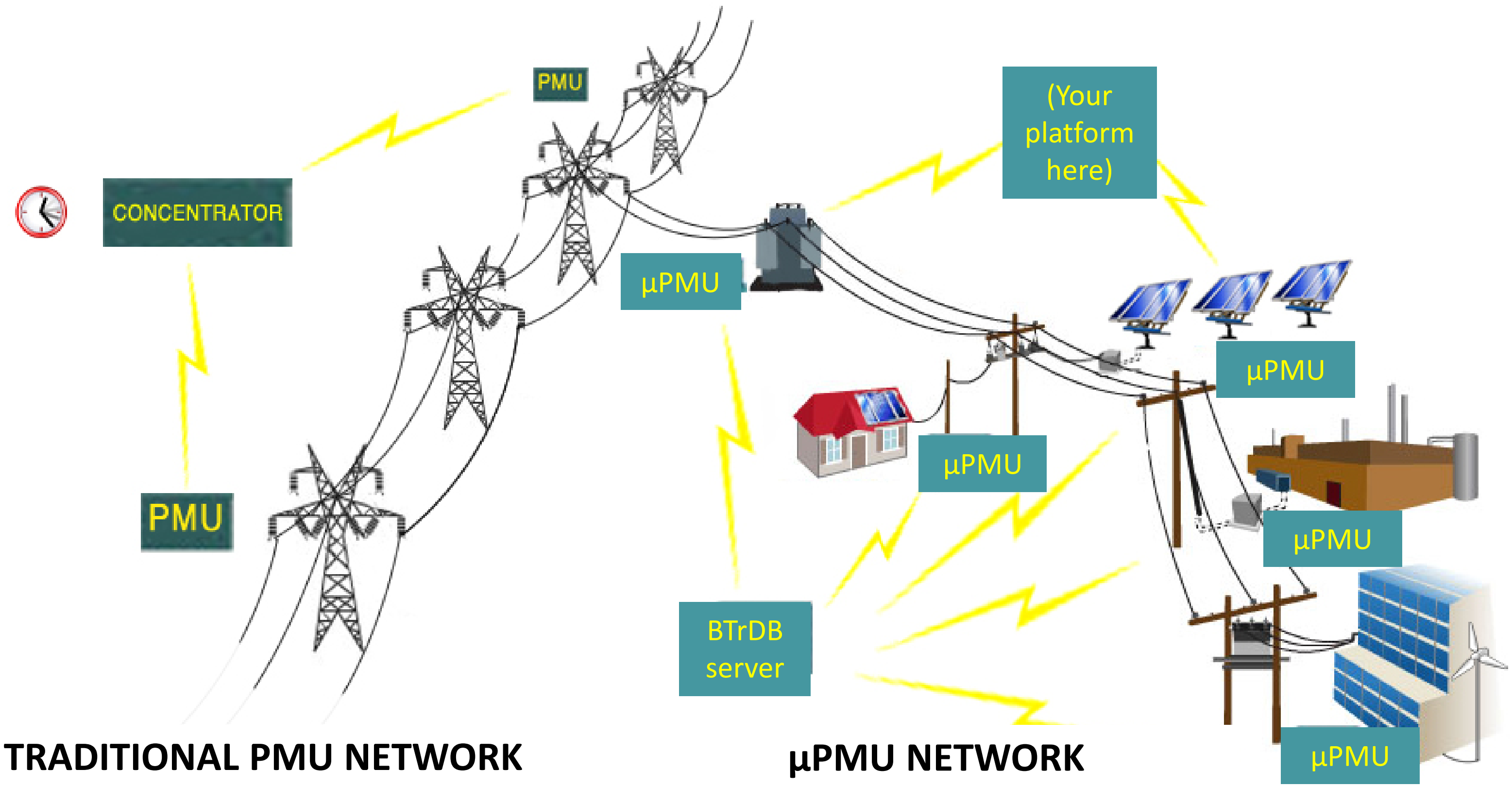
Research partners CIEE, UC Berkeley, Lawrence Berkeley Lab, Power Standards Lab

Field installations at Riverside Public Utilities, Southern California Edison, Pacific Gas & Electric, Alabama Power, Georgia Power, Tennessee Valley Authority

Objective: Explore the value and applications for high-resolution measurements of voltage phasors across distribution systems

Micro-synchrophasor network concept:

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



CONCENTRATOR

PMU

PMU

µPMU

(Your platform here)

µPMU

µPMU

µPMU

BTrDB server

µPMU

TRADITIONAL PMU NETWORK
Transmission System

µPMU NETWORK
Distribution System

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General ARPA-E Project Objectives

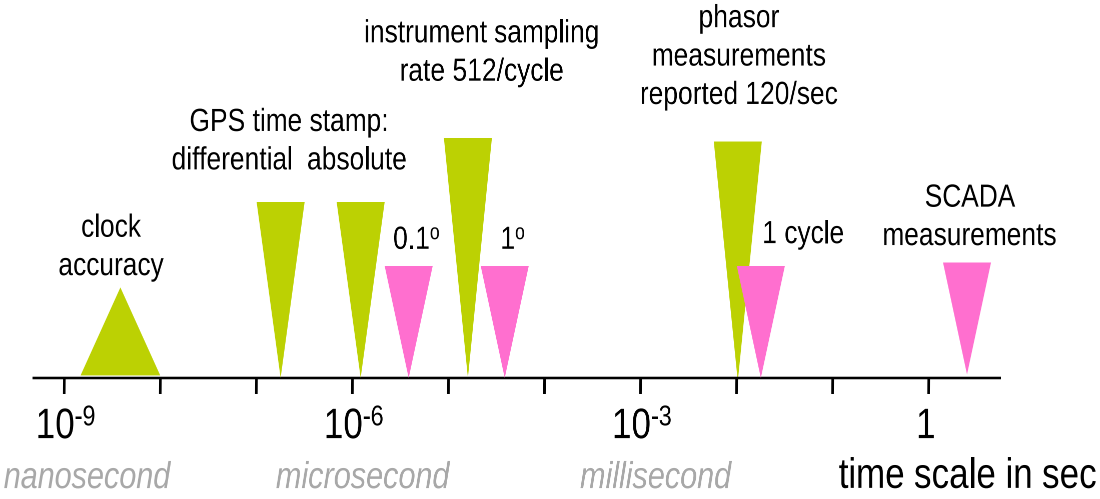
- develop a network of high-precision phasor measurement units (µPMUs) to measure voltage phase angle to within 0.01°
- understand the value of voltage phase angle as a state variable on power distribution systems
- explore applications of µPMU data for distribution systems to improve operations, increase reliability, and enable integration of renewables and other distributed resources
- evaluate the requirements for µPMU data to support specific diagnostic and control applications

Power Standards Lab μPMU

www.powerstandards.com

[cf presentation by Alex McEachern]

- built on PQube3 power quality recorder
- capable of power quality mode with 512 samples per cycle
- time stamping to ns precision, μs 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




PSL


UCB / uPMU Project
Culler / goto@EECS
2
cradlepoint
[redacted]
PSL PQube 3 AC Analyzer
PSL
Power Sensors Ltd
PM1 Power Manager
Current Channels - 333mV, ±10V
Output DC
12V 1.5A
PHOENIX CONTACT
DC OK
STEP POWER
Input AC
100-240V
1A - C2

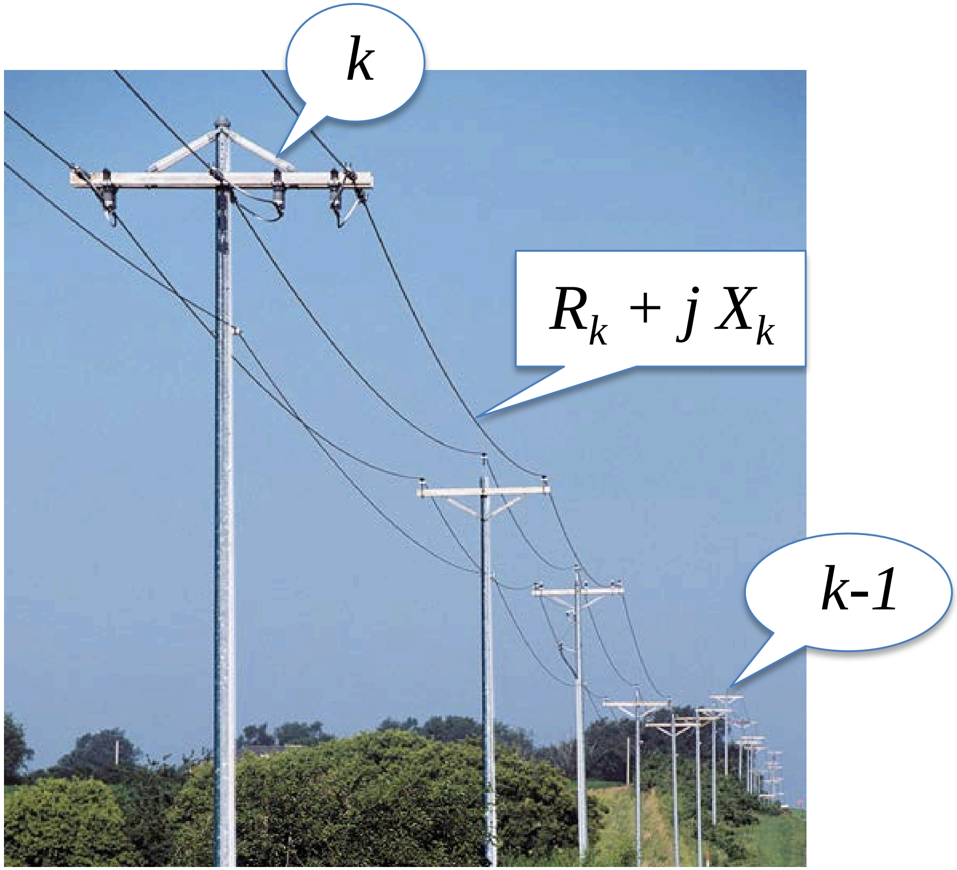
Challenges for distribution synchrophasor measurements, as compared to transmission:

- 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…



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

$$|V_k||V_{k-1}|\sin(\delta_{k-1} - \delta_k) \quad = \quad X_k P_k - R_k Q_k$$

$$|V_{k-1}|^2 - |V_k|^2 \quad = \quad 2(R_k P_k + X_k Q_k) + (R_k^2 + X_k^2)\frac{P_k^2 + Q_k^2}{|V|_k^2}$$

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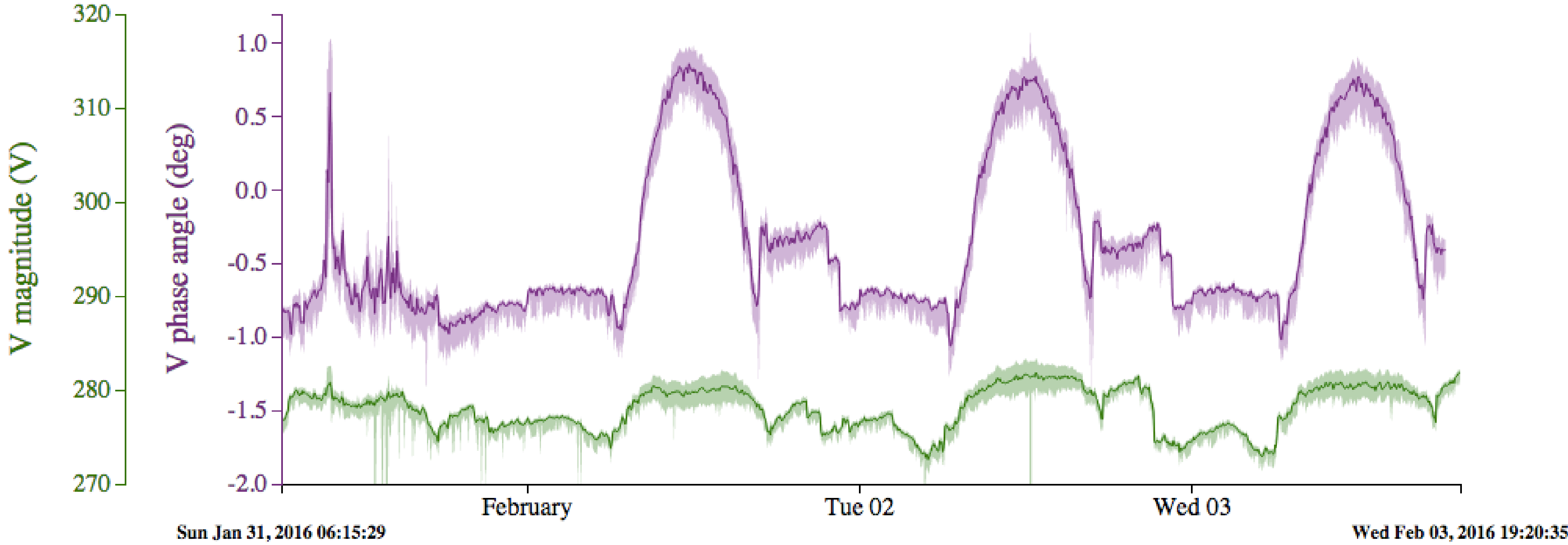
$$|V_{k-1}|^2 - |V_k|^2 \approx 2(R_k P_k + X_k Q_k)$$

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

…but we think this linear approximation will often work for relating voltage phasors to power flow

(Dan Arnold, Roel Dobbe and Michael Sankur, UCB)



µPMU Measurements on a distribution feeder with high-penetration PV, illustrating relationship between voltage phase angle difference and power flow

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Challenges for distribution synchrophasor measurements, as compared to transmission:

Unbalanced three-phase power flow

- Load is not the same on each phase

- Impedance is not the same on each phase

effects of magnetic and electric fields (mutual inductance, cable capacitance) depend on geometry and spacing of conductors, lines are not transposed

Unbalanced three-phase power flow *– Yikes!*

$$
\begin{aligned}
P_{a,k} = {} & \left(\frac{r_{aa,k}}{r_{aa,k}^2 + x_{aa,k}^2}\right)\Bigg(|V_{a,k-1}||V_{a,k}|\left(\cos(\delta_{a,k-1} - \delta_{a,k}) + \frac{x_{aa,k}}{r_{aa,k}}\sin(\delta_{a,k-1} - \delta_{a,k})\right) \\
& - |V_{a,k}|^2 - \frac{|V_{a,k}|}{|V_{b,k}|}\Bigg[\cos\left(\delta_{b,k} - \delta_{a,k}\right)\left(r_{ab,k}P_{b,k} + x_{ab,k}Q_{b,k}\right) \\
& - \sin\left(\delta_{b,k} - \delta_{a,k}\right)\left(x_{ab,k}P_{b,k} - r_{ab,k}Q_{b,k}\right) + \frac{x_{aa,k}}{r_{aa,k}}\cos\left(\delta_{b,k} - \delta_{a,k}\right)\left(x_{ab,k}P_{b,k} - r_{ab,k}Q_{b,k}\right) \\
& + \frac{x_{aa,k}}{r_{aa,k}}\sin\left(\delta_{b,k} - \delta_{a,k}\right)\left(r_{ab,k}P_{b,k} + x_{ab,k}Q_{b,k}\right)\Bigg] - \frac{|V_{a,k}|}{|V_{c,k}|}\Bigg[\cos\left(\delta_{c,k} - \delta_{c,k}\right)\left(r_{ac,k}P_{c,k} + x_{ac,k}Q_{c,k}\right) \\
& - \sin\left(\delta_{c,k} - \delta_{a,k}\right)\left(x_{ac,k}P_{c,k} - r_{ac,k}Q_{c,k}\right) + \frac{x_{aa,k}}{r_{aa,k}}\cos\left(\delta_{c,k} - \delta_{a,k}\right)\left(x_{ac,k}P_{c,k} - r_{ac,k}Q_{c,k}\right) \\
& + \frac{x_{aa,k}}{r_{aa,k}}\sin\left(\delta_{c,k} - \delta_{a,k}\right)\left(r_{ac,k}P_{c,k} + x_{ac,k}Q_{c,k}\right)\Bigg]\Bigg)
\end{aligned}
$$

Dan Arnold and Michael Sankur, UCB

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Challenges for distribution synchrophasor measurements, 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"

Practical Challenge: Transducer errors

- Accuracy of transducers, i.e. potential transformers (PTs) and current transformers (CTs), is much less than the accuracy of the µPMU and limits the obtainable accuracy of both magnitude and angle measurements.

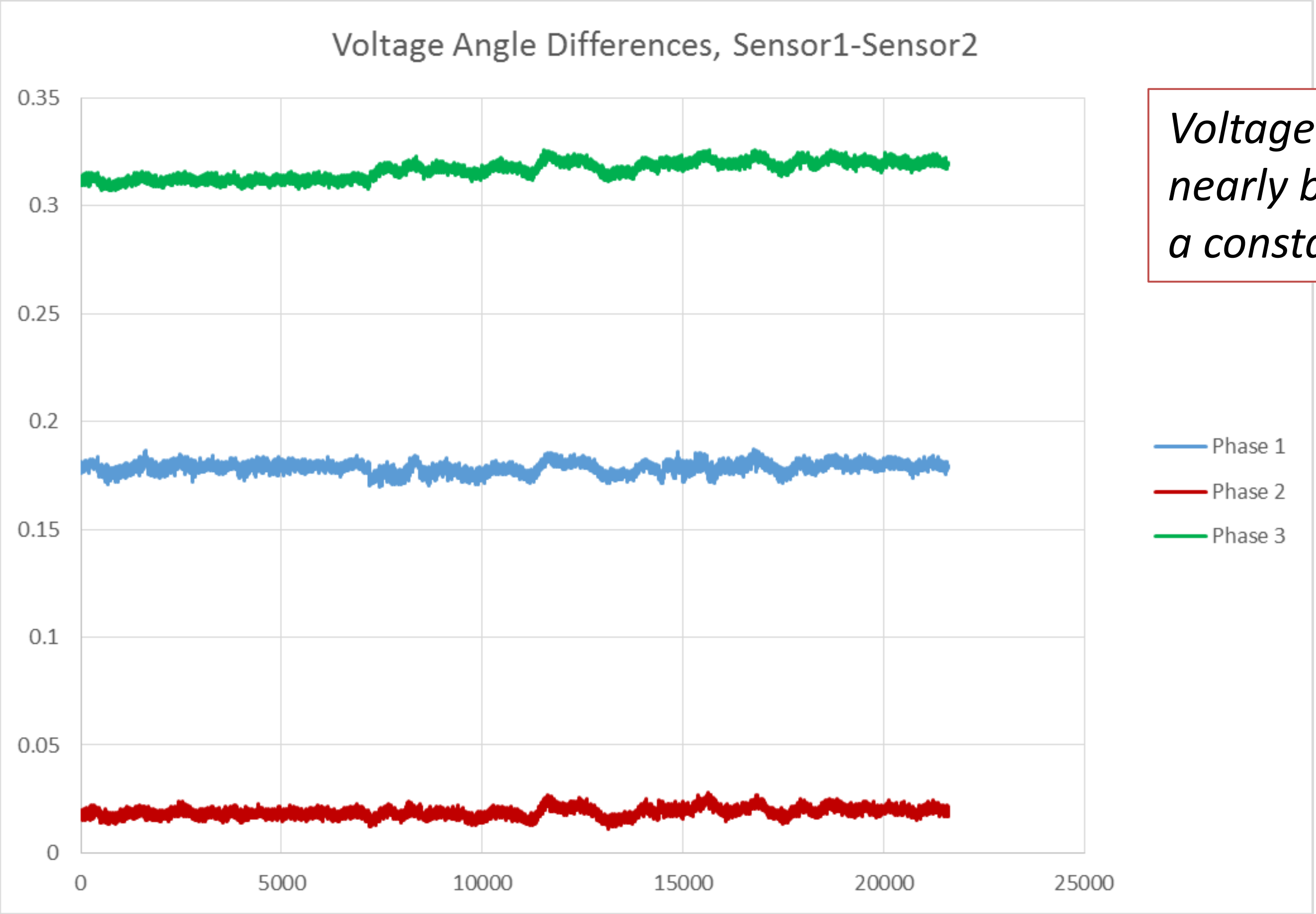
  “Meter grade” instrument transformer is 0.3 Class (0.3% accuracy)

  ➔ overall measurement quality hinges on more than µPMU device

- Ability to measure from behind the service transformer:
  in principle, the voltage phasor on the primary circuit is observable from the secondary side, but transformer under varying load introduces error

Practical Challenge: Transducer errors

Comparison of voltage measurements by two µPMUs connected through different PTs (same make and model) to the same 7.4 kV bus



Voltage angle error is nearly but not exactly a constant offset

Kyle Brady, UCB

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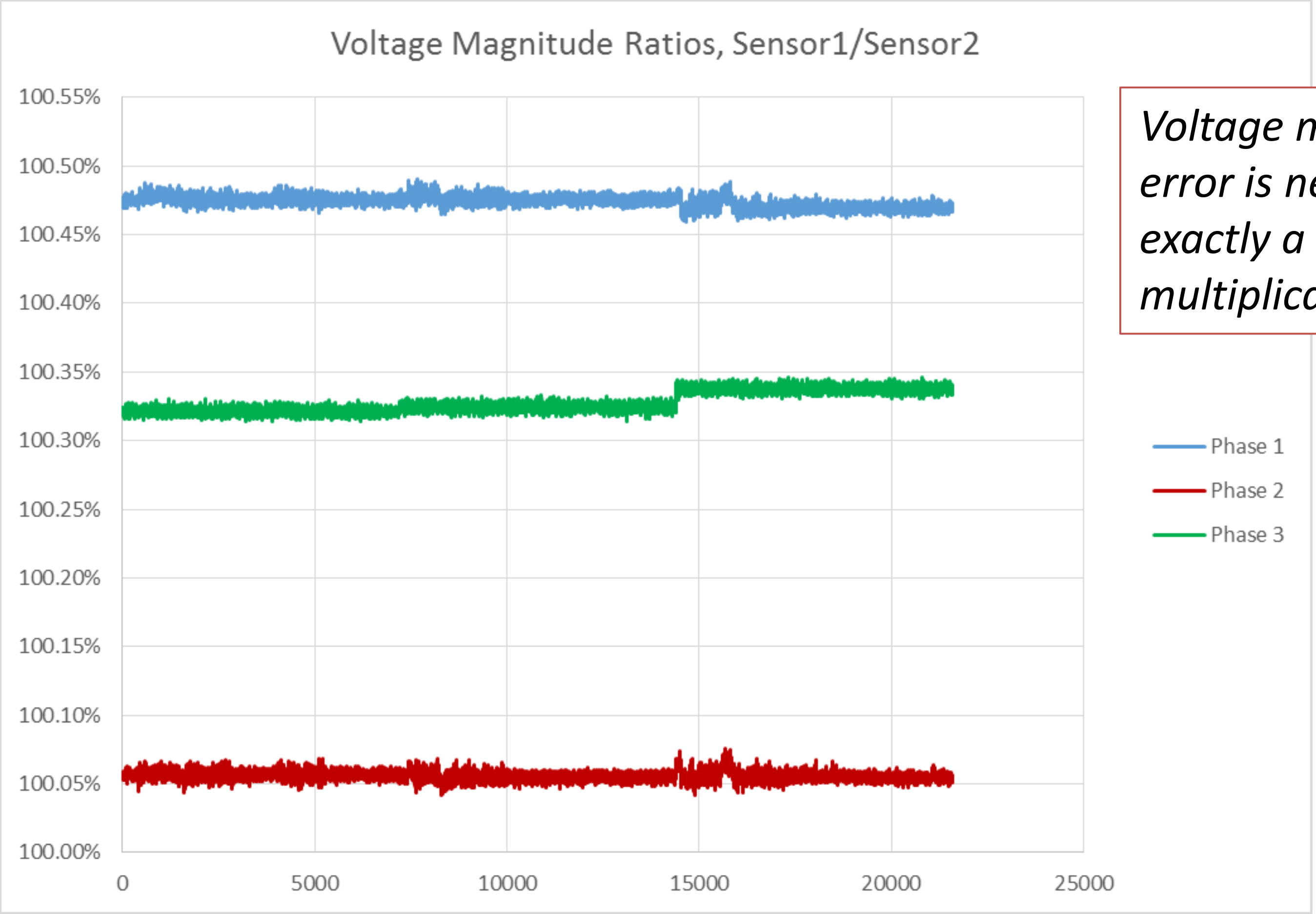
Practical Challenge: Transducer errors

Comparison of voltage measurements by two µPMUs connected through different PTs (same make and model) to the same 7.4 kV bus


Voltage Magnitude Ratios, Sensor1/Sensor2

Voltage magnitude error is nearly but not exactly a constant multiplicative factor

Kyle Brady, UCB

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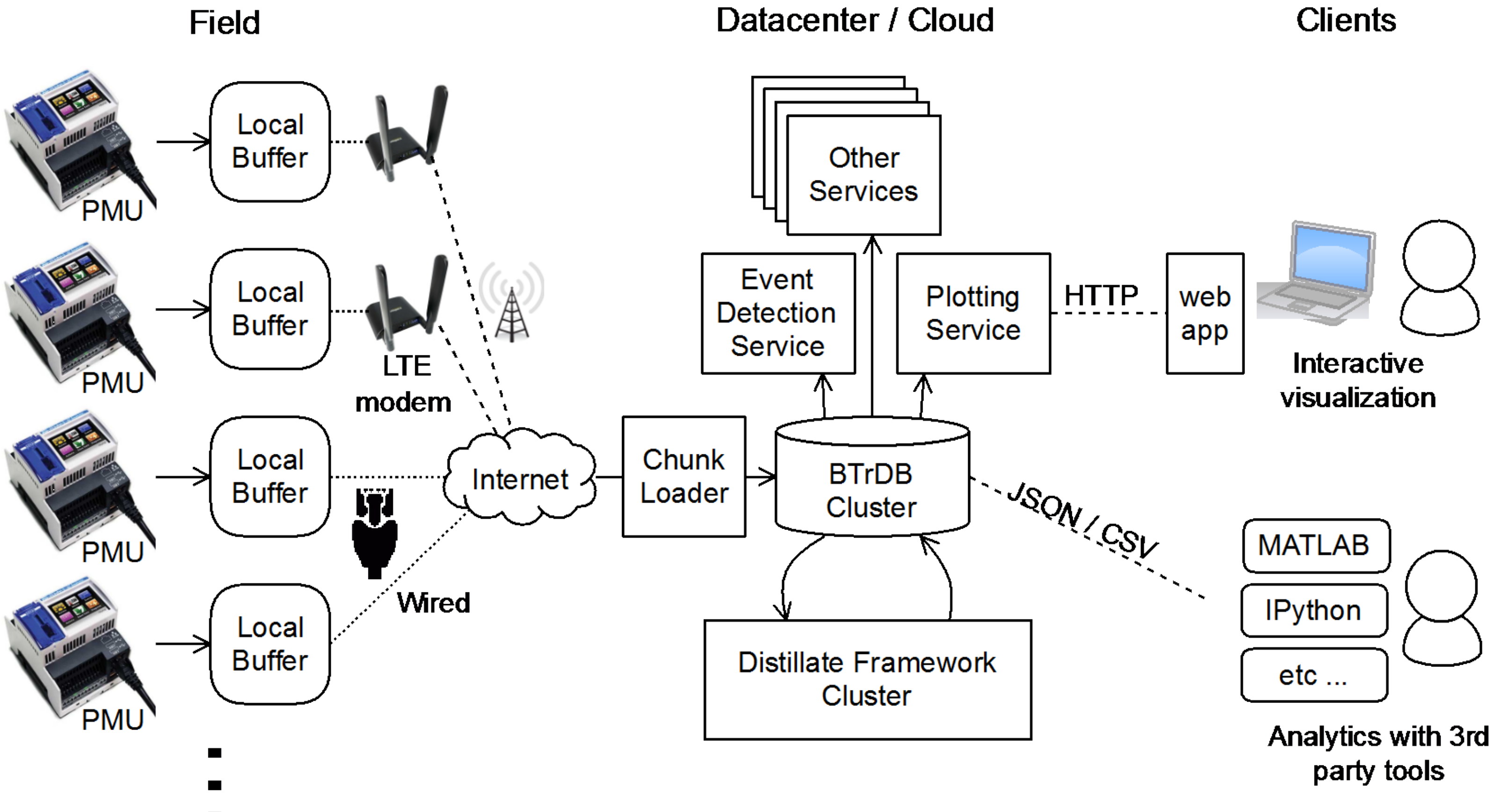
Addressing the Data Challenge: Berkeley Tree Database (BTrDB)



Field

Datacenter / Cloud

Clients

PMU

Local Buffer

LTE modem

Wired

Internet

Chunk Loader

BTrDB Cluster

Event Detection Service

Plotting Service

Other Services

Distillate Framework Cluster

HTTP

web app

Interactive visualization

JSON / CSV

MATLAB

IPython

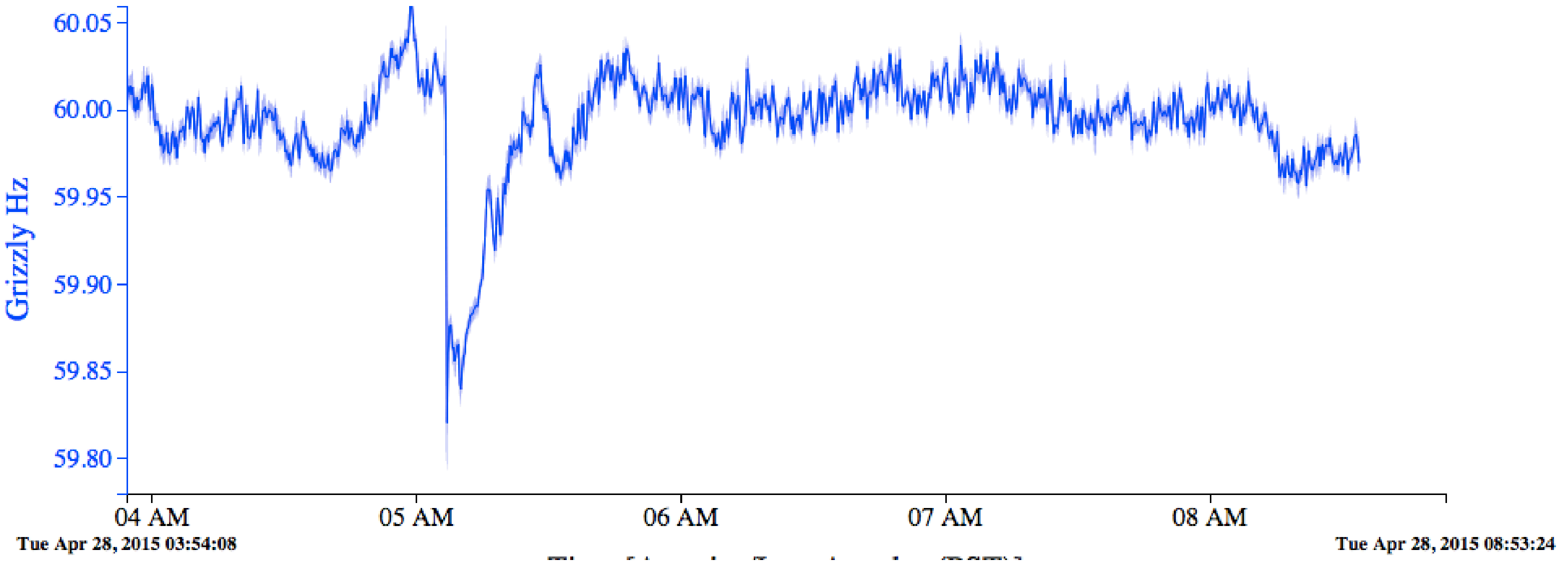
etc ...

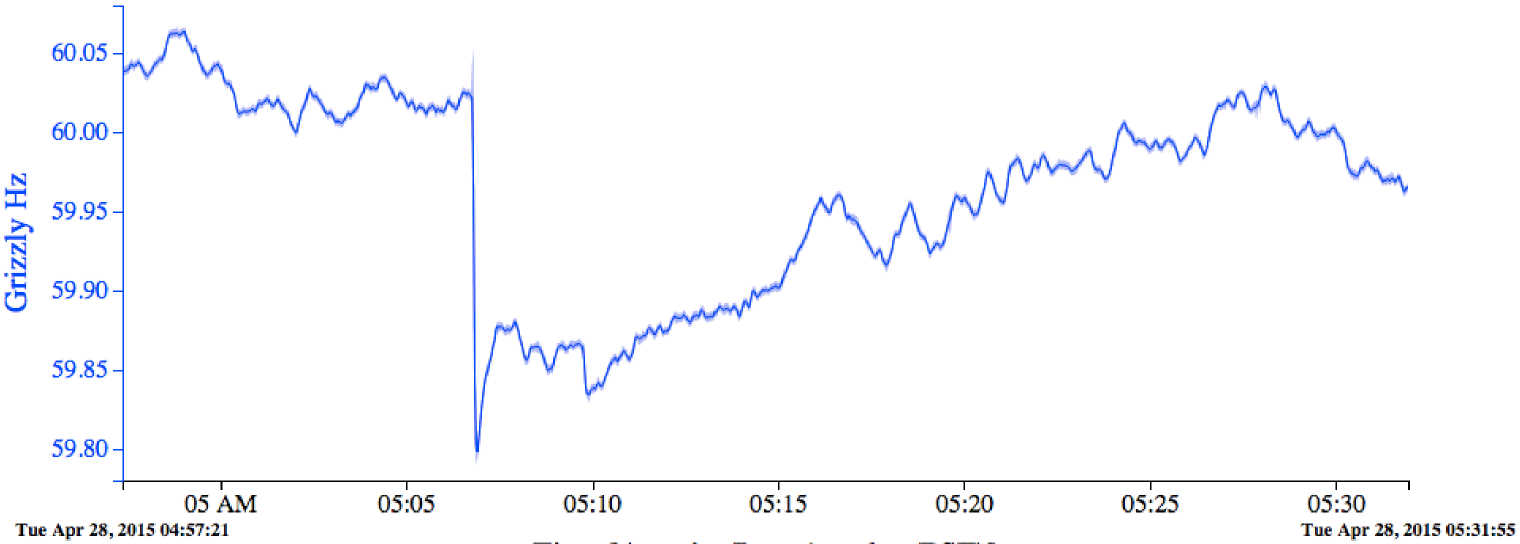
Analytics with 3rd party tools

Michael Andersen, UCB

California Institute for Energy and Environment

Pacific DC Intertie Trip April 28, 2015





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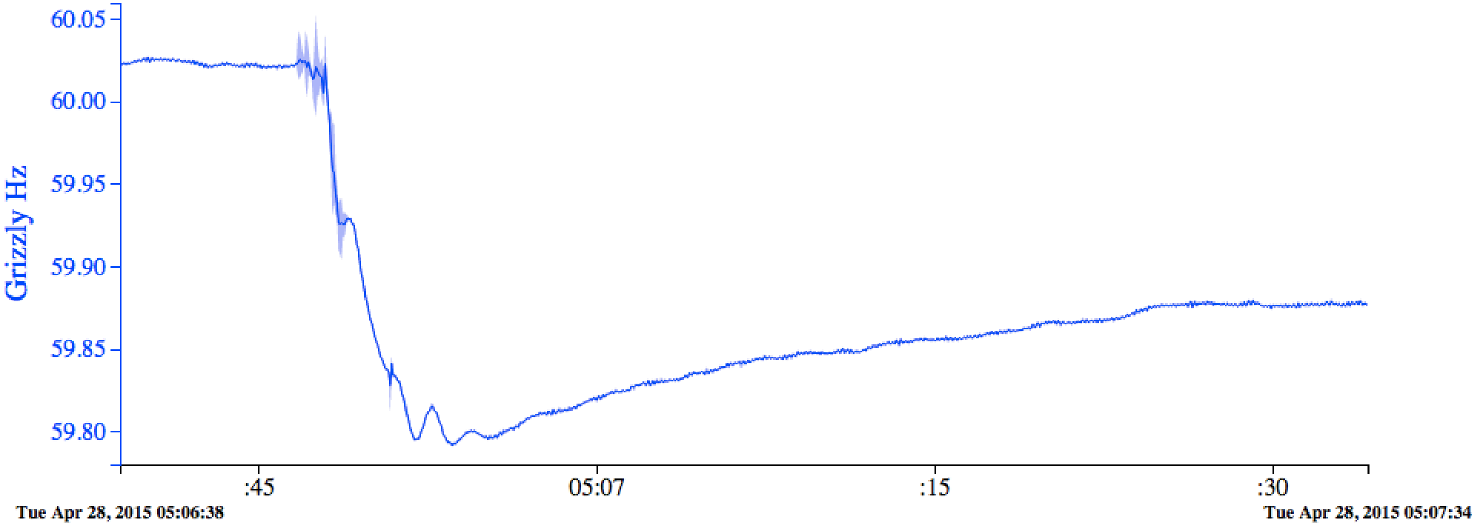

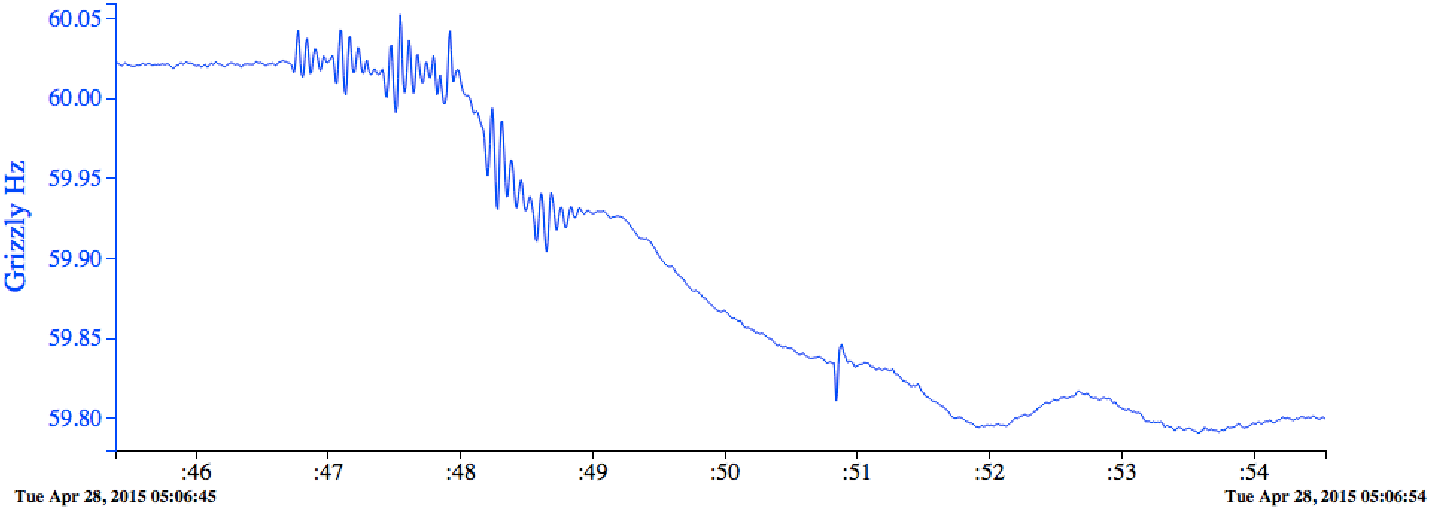

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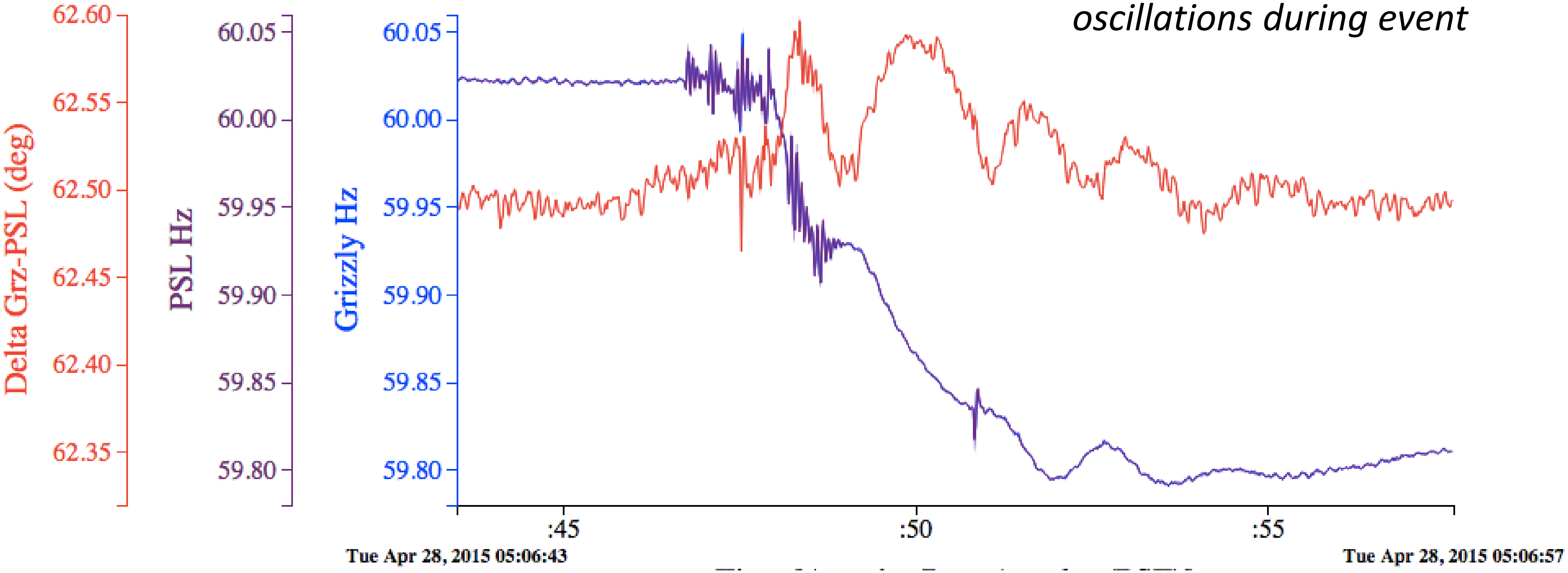
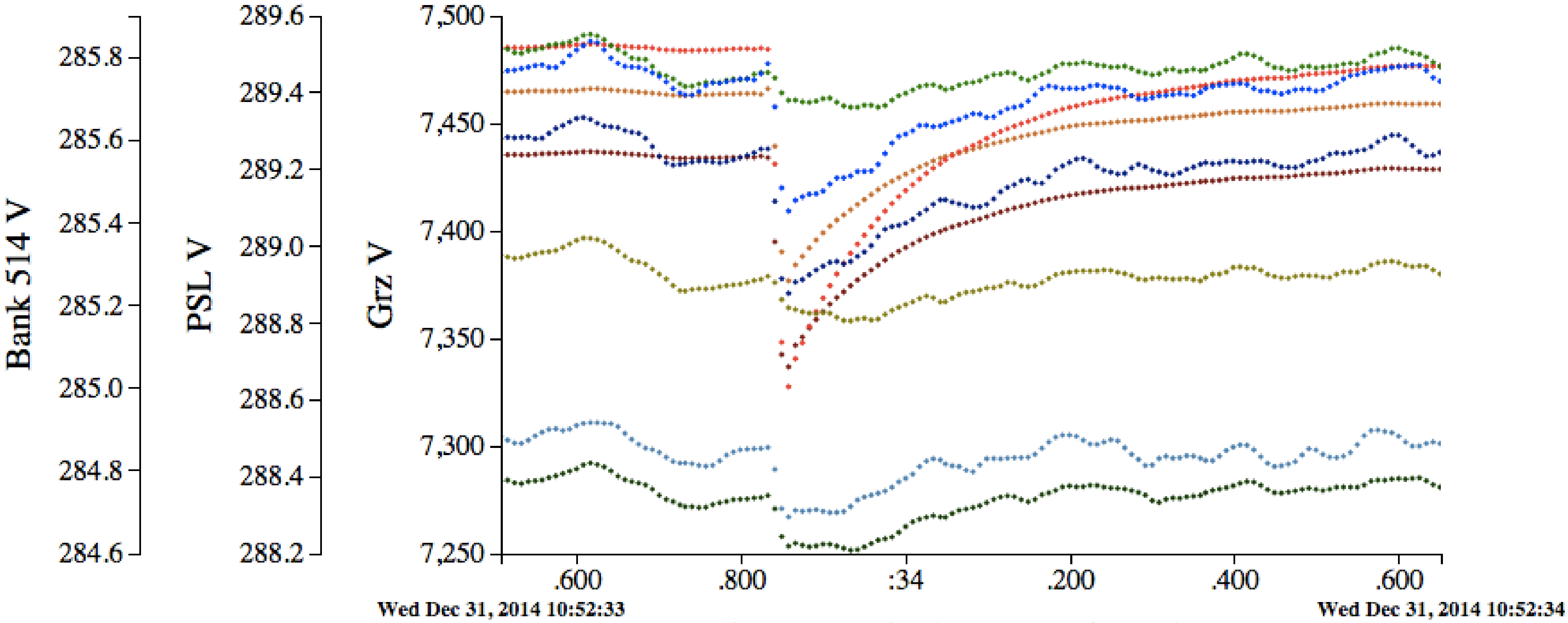
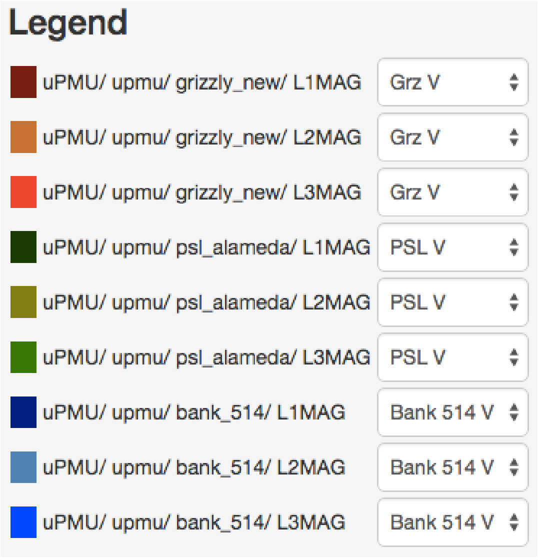
local voltage phase angle oscillations during event







Legend

🟥	uPMU/ upmu/ grizzly_new/ L1MAG	Grz V
🟧	uPMU/ upmu/ grizzly_new/ L2MAG	Grz V
🟥	uPMU/ upmu/ grizzly_new/ L3MAG	Grz V
🟩	uPMU/ upmu/ psl_alameda/ L1MAG	PSL V
🟨	uPMU/ upmu/ psl_alameda/ L2MAG	PSL V
🟩	uPMU/ upmu/ psl_alameda/ L3MAG	PSL V
🟦	uPMU/ upmu/ bank_514/ L1MAG	Bank 514 V
🟦	uPMU/ upmu/ bank_514/ L2MAG	Bank 514 V
🟦	uPMU/ upmu/ bank_514/ L3MAG	Bank 514 V

Voltage disturbance propagation due to arc flash: about 0.0015 p.u. at neighboring transformer Bank 514 and 0.0003 p.u. at PSL

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Distribution Synchrophasor Applications - Overview

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 extremely challenging in practice due to three-phase asymmetry and PT/CT errors that are large compared to changes along a line segment.
- ***PT/CT calibration***. Essential for a subset of applications that depend on highly accurate µPMU measurements at a single point in time to characterize the steady-state of operation ("state estimation based" applications).

Distribution Synchrophasor Applications, cont'd

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.

- ***Linearized DSE:*** Several techniques work in theory. Sensitive to number and placement of µPMUs, and hinges on PT/CT calibration.

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

- ***Residual State Estimation Error:*** requires precise state estimation, see above.
- ***Time-series signature of topology changes***: leverages high-resolution view of transitions.
- ***Source Impedance method:*** a variant of the time-series signature approach.

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.

Distribution Synchrophasor Applications, cont’d

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. *[cf presentation by Emma Stewart et al.]*
- ***Event classification.*** Categorize events, e.g. distinguish locally-caused vs. transmission-level voltage sags by comparing synchronized measurements from different locations. *[cf presentation by Emma Stewart et al.]*
- ***High impedance fault detection***. Distinguish between faults and load changes, e.g. arc flashes and motor starts, by comparing synchronized measurements from different locations.
- ***FIDVR detection***. Fault-induced delayed voltage recovery, due to air conditioners stalling: we haven’t seen one yet, but it’s bound to show up.
- ***Statistical event characterization and learning***. Analysis based on large numbers of rapid queries, made possible by exponential search process. *[cf presentation by Omid Ardakanian]*

Distribution Synchrophasor Applications, cont’d

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:*** *[cf. presentation by Emma Stewart et al.]*
- ***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.
- ***Assess DG impacts on feeder voltage magnitude and volatility.*** Opportunity to apply statistical methods.
- ***Load Characterization***. Assess load volatility and voltage dependence with high-resolution measurements and correlations.

Distribution Synchrophasor Applications, cont’d

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

Control depends a suitable linearization between the phasor profile and P,Q injections for the unbalanced three-phase case.

New Research Involving Micro-Synchrophasors

- Using micro-synchrophasors to detect cyber attacks on substations (DOE CEDS project, under way)

- Using micro-synchrophasors to analyze power consumption in supercomputers (NSA, under way)

- Using micro-synchrophasors to remotely understand commercial AC power grids that surround military installations (DARPA, advanced proposal stage)

- Using micro-synchrophasors to provide input for solar PV and storage control system development (CEC-EPIC)

- Using µPMU data for co-simulation and data integration for solar planning tools (DOE SunShot)

- Using real-time µPMU data for short term planning and operations (DOE Grid Modernization)

- Using micro-synchrophasors to understand geomagnetic disturbance effects on distribution grids and industrial equipment (ARPA-E, proposal stage)

New Research Involving Micro-Synchrophasors, cont’d

- Micro-synchrophasor research with micro-grid control manufacturers (various projects getting started)
- Micro-synchrophasor research with wind turbine and solar inverter manufacturers (various project proposals are developing)
- Micro-synchrophasor research in
    - Japan (various universities)
    - China (State Grid)
    - Europe (universities, national labs, and utility R&D)
    - Latin America (proposed at various universities)
    - Africa (starting at various universities)
    - Middle East (proposed)
    - Central and South Africa (various proposed projects)

Research Needs and Opportunities

- Develop, test and refine specific diagnostic tool sets ready for field implementation
- Move from event detection and forensics to event anticipation
- Transducer (PT & CT) calibration
- Leveraging the distillate structure: apply interactive analytics and machine learning tools for a new diagnostic paradigm
- Build and enhance platforms for integrating heterogeneous data streams
- Explore control applications, especially for distributed energy resources, in simulation environments and small pilot studies
- Algorithm extensions to the three-phase unbalanced case

You know where to find me:

vonmeier@berkeley.edu

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