Team

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Distribution Phasor Measurement Units

Funded Projects
ARPA-E Project: Micro-Synchrophasors for Distribution
Cybersecurity for Energy Delivery Systems: Intrusion detection and visualization with distribution synchrophasors

Utility and field site partners
Southern California Edison, Sacramento Municipal Utility District, Southern Company, UC San Diego, Riverside Public Utility, NEETRAC

Approach
• Develop a network of high-precision phasor measurement units (μPMUs) to measure voltage phasors with unprecedented accuracy (~ 0.01°) – Power Standards Laboratory
• Study diagnostic and control applications for μPMU data on distribution systems and develop suitable algorithms including load identification and impedance calculation
• Challenges include multiple sources of measurement error and noise: learning what matters
• Performance metrics include angular resolution, overall accuracy, latency; key objective is to match data quality with applications
• Develop useful, practical tools for a new type of visibility and management of distribution circuits

Research Question: Can synchronized distribution level phasor measurements enhance planning for power flow and system control, security and resiliency in the modernized grid?
Background

Vision for a future electricity grid in California and the U.S. involves increasing the use of renewable generation on the distribution grid.

With large numbers of distributed generation units, including solar PV, the future grid will have more complex analysis needs and development of new control architectures.

The distribution system has more components than the transmission system and therefore more unknowns and potential for error in models.

– Growing number of measured and grid model data sources becoming available
– They must be accurate, and interpreted correctly.
– Errors in data are more prevalent in the distribution system

To facilitate high penetration of DG, measured and modeled representations of generation must be accurate and validated, giving distribution planners and operators confidence in their performance
Accomplishments

Demonstrated \( \mu \)PMU device performance on lab bench

Installed and networked prototype \( \mu \)PMUs at Berkeley Lab pilot site with 4G wireless communication

Debugged hardware, firmware, installation design

Built scalable database and plotting tool “Quasar 2.0” for fast and flexible access to high-resolution time-series data

Prepared detailed installation plans with host / partner utilities at four field sites, targeting different applications

Analyzed requirements and use cases for a broad spectrum of diagnostic and control applications

Developed theoretical algorithms for topology detection, state estimation, fault location based on \( \mu \)PMU data
Installed μPMU devices in 4 locations at LBNL – from substation (feeder head) to Building 71
Coupled with existing measurement system on site
Measuring high fidelity voltage and current magnitude and phase angle (512 samples/cycle)
Developed LBNL system model and advancing research in model validation and calibration
Preliminary challenges include communications, calibration, and commissioning of sensors

New Work: Early detection system for grid-network cyber attacks working with Computational Research Division
How do we know what it is & what it means?
**Time Series Synchronized Data Visualization from Distribution μPMUs**

- Synchronized magnitude measurements reveal phenomena common to different measurement locations.
- Distribution impacts can be visualized on the transmission system and vice versa.
- Data can be utilized to characterize load and generation behavior precisely.
Example: What is this?
Orinda Fault (Oct 5) Grizzly V & I

Legend
- uPMU/upmu/grizzly_new/C1MAG (Current (A) ↓)
- uPMU/upmu/grizzly_new/C2MAG (Current (A) ↓)
- uPMU/upmu/grizzly_new/C3MAG (Current (A) ↓)

Legend
- uPMU/upmu/grizzly_new/L1MAG (Voltage Mag (V) ↓)
- uPMU/upmu/grizzly_new/L2MAG (Voltage Mag (V) ↓)
- uPMU/upmu/grizzly_new/L3MAG (Voltage Mag (V) ↓)
Voltage phase angle difference (green) and current (violet) between two locations on a 12kV cable, seen at greater resolution.
Empirical data analysis: identify phases, power flows, interpret events…

What’s hard: small signal-to-noise ratio, identifying error sources (e.g. PTs & CTs)

Validate circuit models: calculate impedances

Pilot site has short, lightly loaded, asymmetrical underground cables

Modify installation plans to allow more simple, direct validation at some locations

It’s hard to ground-truth field data absent other good instrumentation
Proceed with field installations

\textit{Must address diverse utility criteria for hardware specs, tailor peripherals and placement strategy to specific environments, manage expectations}

Integrate new \(\mu\)PMU data streams and implement distillates on Quasar

Perform state estimation and topology detection algorithm computations offline in Matlab environment

As an alternate method, integrate C37.118 \(\mu\)PMU data stream with OSIsoft PI server, compatible with existing tools

Continue theoretical work on control applications
Final Year Objectives

Complete field installations at manageable scale
Demonstrate empirical µPMU data provide useful, actionable intelligence about the distribution system
Exercise topology detection and state estimation algorithms with field data, evaluate performance
Test algorithms for decentralized control of distributed resources based on µPMU measurements in simulation environment
Identify most promising and fruitful directions for follow-on research, development and demonstration
Applications Being Studied

- Model Validation: compute impedances between instrumented locations and compare to circuit models
- Phase Identification: confirm ABC labels using phase angles and time-series correlations
- Load identification: Determine key parameters of distributed load for modeling
- Characterizing dynamic behaviors of loads, distributed generation and system interactions
- State Estimation: integrate μPMU measurements with available SCADA and load data (“pseudo-measurements”) in a fast, linearized method for estimating state variables at non-instrumented nodes
- Topology Detection: use characteristic signatures of time-series phasor measurements to recognize changes in topology, e.g. to confirm switch opening or closing.
- Non-model based control of distributed resources: use phasor measurements for a robust indication of real and reactive power flows throughout the network
Impact of Accuracy in DG Models and Related Barriers

Inaccurate distribution circuit models over- or underestimate DG impacts, resulting in:

- Excessive cost to utilities and customers from unnecessary mitigation measures
  - Example: modifications to protection systems, voltage regulation and power quality management to compensate for presumed impacts
- Inhibited DG deployment
  - Example: presumed feeder hosting capacity is reached
- Compromised safety and power quality
  - Example: DG presumed harmless actually results in voltage violations, reverse power flow and/or disruption of utility protection scheme

From a planning analysis standpoint, there are three related barriers to the integration of renewables to the distribution grid:

- The lack of tools to adequately represent high penetration levels and advanced control strategies for distributed resources;
- The lack of accuracy and trustworthiness of models, often due to limited availability of data for their validation; and
- The limited accuracy of measured data sources in and of themselves, for control and validation purposes
Error Sources

Possible sources of signal and noise

- Physical system
  - PTs & CTs
  - µPMU filters
- Analog µPMU channel input
  - µPMU calibration
  - µPMU sampling
  - µPMU reporting
- µPMU data on device
- µPMU data in database
  - Communication and data logging
  - Representation in model
- µPMU data integrated to model
  - Model Representation

Normal Accuracy for Relay and Instrumentation
- 0.3 Class PT
- 1.2 Class CT

High accuracy device and logging
- 1% TVE, 0.02 magnitude error
- 0.5% magnitude error
### Expected data requirements for key applications

<table>
<thead>
<tr>
<th>Topology/Connectivity</th>
<th>Sampling Rate (per cycle)</th>
<th>Angle Resolution (milli-deg)</th>
<th>Spatial Resolution (placement)</th>
<th>Data Volume (bandwidth)</th>
<th>Communication Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady State Circuit Behavior (e.g. voltage profile)</td>
<td>1-2</td>
<td>10-300</td>
<td>Sparse</td>
<td>Medium but continuous</td>
<td>Typically low but depends on application</td>
</tr>
<tr>
<td>Dynamic Circuit Behavior (e.g faults and motor starting)</td>
<td>2-512</td>
<td>10-50</td>
<td>Dense</td>
<td>High but intermittent (triggered on event)</td>
<td>Typically but depends on application</td>
</tr>
</tbody>
</table>
Expected Outcomes

- ARPA-E project completion – April 2016
- CEDS – just started
- Demonstrate empirical μPMU data provide useful, actionable intelligence about the distribution system
- Exercise topology detection and state estimation algorithms with field data, evaluate performance
- Integrate C37.118 μPMU data stream with OSIsoft PI server, compatible with existing tools, and commonly used at utilities
- Test algorithms for decentralized control of distributed resources based on μPMU measurements in simulation environment
- Identify most promising and fruitful directions for follow-on research, development and demonstration
Conclusions

Distribution synchrophasors are an idea that is resonating well throughout research community and industry, esp. in California

Scary data volume (terabytes) can be handled effectively

Practical implementation of field measurements faces mundane, time-consuming hurdles

Key remaining challenges for measurement accuracy reside outside, not inside μPMU

Many advanced application opportunities appear worth exploring
Thank You

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