2016 Smart Grid R&D Program
Peer Review Meeting

Micro PMU Framework
For Model Validation
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Micro PMU Framework for Model Validation

Objectives & Outcomes

Objectives:
Address fundamental barriers to improving accuracy of distribution planning models with new data sources
Utilize advanced sensor data to develop a framework for validating key distribution model errors to advance a microgrid and high penetration of DER future

Outcomes:
Methodology for validating key components, and/or determining when investigation of errors is necessary, implemented at Riverside Public Utilities

Life-cycle Funding Summary ($K)

<table>
<thead>
<tr>
<th>Prior to FY 16</th>
<th>FY16, authorized</th>
<th>FY17, requested</th>
<th>Out-year(s)</th>
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<tr>
<td>220k</td>
<td>0</td>
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Technical Scope

1) Develop and analyze case studies that highlight critical validation issues in conjunction with partner utilities – including renewables interconnection and power flow studies
2) deploy a network of distribution PMUs in key “error” locations
3) develop and implement validation method including load magnitude, load types, conductor type and impedance and topology
4) develop a extensible framework for validating power flow models in distribution in a standardized manner
Motivation and Problem Outline

- Distribution Planning Engineers use electrical models for analyzing planned upgrades, Load transfer studies, Interconnection review, Capacity planning
- In future these models are also to be used for visualization of performance, high penetration of DER integration/control, shorter term studies, emergency and outage management and shorter term planned switching and load transfer studies
- Planning is reliant on the accuracy of models to determine best path forward for distribution future
- Prevalent errors in model data mean quality and cost of power delivered could be compromised
  - Possible under or over compensation
  - Overly conservative planning
Current Practice in Model Validation During Interconnection

- Current practice is rudimentary yet has been sufficient
  - Engineer will check feeder status
    - Manual
    - Field crews
    - Reporting sensors
- Load verified against aggregate customer information or substation
- Validation generally based on last best known status
- More detailed load models are generally selected as default
- Controllable equipment is as was set – i.e. as designed, not “as performing”
- Sensor and Monitoring investment is normally in response to an incident
  - i.e. 2003 NA Outage led to synchrophasor investment
- Instrumenting all nodes on distribution system is infeasible
- Cost of maintenance is increasing as the system ages
- Less conservative approaches for Distribution management are desired
- Simulation is the only way to plan for this – but needs to be accurate
- Actionable Measurement and analytics is the key
Practical & Quantitative Impact of Errors on Customers and Utility

• Inaccurate distribution circuit models over- or underestimate DG impacts, resulting in
  – Excessive cost to utilities and customers from unnecessary mitigation measures
    • Example: Addition of expensive voltage compensation to a feeder to allow for more PV to be integrated based on analysis with incorrect impedance, cost is either to the utility or the customer
  – Inhibited DG deployment
    • Example: During initial analysis of a feeder at RPU, it was assumed that the 7.5MVA peak load, based on limited SCADA, meant that level of PV could be installed without risking significant backfeed at the substation. After further analysis. Had the 7.5MW been installed, there would have been backfeed at minimum load times. Time series analysis showed need for conductor upgrades. The installation was reduced to 5MW.
  – Compromised safety and power quality
    • Example: DG presumed harmless actually results in voltage violations, reverse power flow and/or disruption of utility protection scheme, meaning is may mis-operate during a fault and cause damage
# Common Distribution Models Feature Errors and Impact

<table>
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<tr>
<th>Area</th>
<th>Impact</th>
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<tr>
<td>Line &amp; Source Impedance</td>
<td>Incorrect interpretation of impact of DG interconnection for example power quality impacts Voltage regulation errors</td>
</tr>
<tr>
<td>Topology Error</td>
<td>Unplanned outage due to unknown status of switch during load transfer Inefficiencies in operations due to need of field crew to physically check status</td>
</tr>
<tr>
<td>Phase Identification</td>
<td>Unbalanced system, increased losses, protection and voltage regulation errors</td>
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<tr>
<td>Load Magnitude</td>
<td>Error and unplanned overloads during load transfer studies Inefficient use of resources Inhibited DG deployment due to under or over estimation of load Power Quality issues</td>
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Distributed PV Integration is a Key Motivating Factor

Circuit Peak is 4 hours later than predicted PV Peak on selected feeder

- Vision for a future electricity grid in California and the U.S. involves increasing the use of renewable generation on the distribution grid.
- 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 input 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
Collaborations: Riverside Public Utility

- Publicly Owned Electric and Water Utility
- Population - 311,896
- Service Area - 82 square miles
  - Substations – 14
  - Transmission Lines
    - 91 Circuit Miles
  - Distribution Lines
    - 1,323 Circuit Miles
  - Electric Meters – 107,500
- Record peak demand of 612 MW on 9/14/2014
- 2014 – Total of 13 MW installed PV, 2015 >20MW
- Limited visibility into distribution system and a number of known validation issues, including time series minimum load conditions unknown, impedance and topology
Riverside Public Utility μPMUs

PV Site - 7.5MW

Substation

μPMU 1

μPMU 2
Micro-Phasor Measurement Units (µPMU): (Developed by Power Standards Lab via ARPA-E)

- **Approach**
  - Develop a network of high-precision phasor measurement units (µPMUs) to measure voltage phasors with unprecedented accuracy (~ 0.01°) – Power Standards Laboratory
  - Performance metrics include angular resolution, overall accuracy, latency; key objective is to match data quality with applications
  - Goal of these projects is to 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?

Devices developed by PSL through funded Projects

ARPA-E Project: Micro-Synchrophasors for Distribution

Cybersecurity for Energy Delivery Systems: Intrusion detection and visualization with distribution synchrophasors

Collaborators, Utility and field site partners
CIEE, PSL, Southern California Edison, Sacramento Municipal Utility District, Southern Company, UC San Diego, Riverside Public Utility, NEETRAC
SCADA versus the μPMU

Conventional measure does not see the spike or indication of momentary short circuit.

Motor Start

Current step up after transient: anomaly (DER behavior)

Conventional measure does not see the spike

4 second delay before step

uPMU measures 10 x current transient
Tasks and Technical Scope Summary

• RPU has defined requirements and analysis that must be conducted for interconnection of distributed PV
• Each of these stages requires utilization of a distribution planning model
• We will use this process to define the types of analysis that may have errors and the technical and financial impact it would have on each area
• Task 1: Sensor deployment, case study development and data collection
  – Funded via ARPA-E – Deployed 6 sensors at RPU, data collected via BTrDB (custom open source time series DB)
• Task 2: Impedance validation
  – Modeled and measured analysis of transformer and line impedance, determined impact on range of impedance errors across feeder
• Task 3: Topology and Identification of load magnitudes
  – Analysis of voltage dependency and steady state magnitude validation
  – Determined operational topology changes with μPMU data
• Task 4: Framework Development and Reporting
• **Deliverables: Technical report – October 2016**
Outline of Technical Scope

• Validation issues addressed
  – Line impedance
  – Load model and voltage dependency
  – Topology and source impedance

• For the three most prominent issues determine
  – A) impact of error within steady state distribution planning realm
  – B) apply method utilizing μPMU data to validate and/or calibrate
  – C) determine gaps in analysis and possible dynamic impact
  – D) framework for repeatable application
Validation Parameter 1: Impedance

- Potential Impacts of Incorrect Impedance
  - Incorrect state estimation
  - Incorrect protection settings
  - Interconnection impact – incorrect voltage analysis

- Reasons for Incorrect Impedance in planning model
  - Impedance can degrade over time
  - Incorrect cable/conductor type

Primary impact of impedance error is incorrect bus voltages and power loss errors for feeder
Can result in sub-optimal operation of resources on feeder
With a 15% average error in impedance – maximum voltage difference is ~1.5% from base case, outliers vary by approximately 5%
Loss error increases by ~1% point
Method of applying μPMU data to calculate correct impedance for RPU feeder

- Impedance Calculation at RPU
  - Least squares method

\[
\vec{V}_{sub} - \vec{V}_{PV} = \hat{Z}_{sub} \vec{I}_{sub}
\]

\[
\hat{Z} = \begin{bmatrix}
Z_{AA} & Z_{AB} & Z_{AC} \\
Z_{AB} & Z_{BB} & Z_{BC} \\
Z_{AC} & Z_{BC} & Z_{CC}
\end{bmatrix}
\]

\[
\begin{array}{ccc}
0.523 + 1.135j & 0.146 + 0.387j & 0.146 + 0.387j \\
0.146 + 0.387j & 0.593 + 1.24j & 0.10 + 0.29j \\
0.146 + 0.387j & 0.146 + 0.387j & 0.523 + 1.135j
\end{array}
\]

\[
\begin{array}{ccc}
0.5 + 1.29j & 0.12 + 0.37j & 0.21 + 0.18j \\
0.12 + .37j & 0.59 + 1.24j & 0.10 + 0.29j \\
0.21 + .18j & 0.10 + 0.29j & 0.45 + 1.08j
\end{array}
\]

- Outcome: Impedance on line is ~10% less than modeled
  - If extrapolated - results in error of 1% in simulated bus voltages
  - Possible impact – in this case voltage is operating on the edge of standard, could require change in regulation settings
Validation Parameter 2: Load Models

- Impact: Accurate estimates of voltage dependency of loads are important for distribution planning
  - Incorrect assumptions have been shown to compromise the usefulness of planning studies
- Yet, voltage dependency is difficult to estimate
  - Complexity set to increase with PV penetration
  - μPMU’s offer potential to accurately estimate dependency
Method of Validating: Fitting of Dynamical Load Response with μPMU data

- Exponential Recovery Load Model
  - Model fit during non-generation hours

\[ T_p \dot{x}_p(t) = -x_p(t) + P_0 \left( \frac{V(t)}{V_0} \right)^{\alpha_s} - P_0 \left( \frac{V(t)}{V_0} \right)^{\alpha_t} \]

\[ P_d = x_p(t) + P_0 \left( \frac{V(t)}{V_0} \right)^{\alpha_t} \]
Application of validated load model to both daytime and nighttime load

- During the day, dominant penetration of inverter generation, gives transient response to step in voltage – Unsuitable to fit dynamic load model
- Steady state model is adequate for understanding steady state response during generation hours – Useful for Conservation Voltage Reduction (CVR)
- Opportunity for future work
Validation Parameter 3: Source Impedance Analysis for Determining Topology Change

- Topology change verification rather than validation of existing topology
- μPMU located on secondary side of transformer
  - Source impedance dominated by transformer
- Baseline Z transformer magnitude = 0.0088

\[
Z_{\text{Thevenin}} = \frac{V}{I}
\]
Feeder reconfiguration and related source impedance changes

- Power flow change indicative – good for when have directly connected μPMU

- For sparse measurements - Source Impedance calculated from real time data as seen from PV site

- Can see clear change in source impedance for configuration change
Future Framework for Model Validation with μPMUs
Lessons Learned

• The key items we will learned include:
  – Quantification of technical impact of common issues
  – Determine level of “correctness” needed for common planning tasks including DER interconnection

• Requirements for a framework for model validation for different types of distribution planning analysis in future
  – Determine other key errors driving inefficiencies

• Benefit of utilizing high fidelity data versus SCADA and smart metering, what type, accuracy and latency of data do we require to accurately validate models to required levels
Outcomes

- Determined range of validity for line and source impedance, and load type selection
- Project quantified technical impact of inaccurate information currently used in distribution planning studies
- Determined accuracy requirements for common planning tasks including DER interconnection
- Established the comparative value of distribution PMU data for these objectives versus other sources of distribution data including SCADA and smart metering
- Publications
- New NASPI working group on distribution PMU’s – kicking off in Oct
Looking Ahead

• Follow on projects
  – Cyber-Security with \(\mu\)PMUs (CEDS) – applying methods developed here to determine state of system and equipment
    • Optimal sensor placement tool for validation and verification of events
  – Philadelphia Navy Yard – application of validation methods for model build
  – ADMS GMLC – model validation framework for DMS – model validation module will be integrated to commercial platform

• Future Research Topics
  – Real time feeder and equipment state analysis - degradation and feeder mean time to failure analysis – predicting transformer failure analysis
  – Dynamic inverter/DER/microgrid model validation
  – Planning model real time data integration
  – Predictive and risk based islanding and protection of microgrids
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Back-up Slides
1) ARPA-E Project: μPMU for Distribution

- Project is developing and deploying the μPMU devices and developing and testing use case with utilities.
- Riverside PU are now deploying 10 x devices funded through the ARPA-E project and will be used for model validation here. Initial communication and deployment plan has been ironed out in this project and now applies to the RPU deployment. Data will be initially collected in the visualization platform in this project and then transferred to the preferred data collection platform for RPU (OSISoft). Communications and Device cost funded by ARPA-E, Peripherals funded by model validation project.

2) CEDS Project: Supporting Cyber Security of Power Distribution Systems by Detecting Differences Between Real-time μPMU Measurements and Cyber-Reported SCADA

- Use physical measurements from μPMUs to detect cyber attacks against the distribution grid aiming to (1) disrupt safe and normal operation of substation components or (2) mask consequence of malfunctioning substation components. The team will model expected state of distribution grid and determine appropriate locations to capture distribution network readings in order to detect deviations. Compare this to cyber traffic received to investigate possible cyber cause.
- Initial stages of this project involve integration of μPMU data with the OSISoft data platform, initially utilizing LBNL data and then once proven utilizing the RPU data. OSISoft is being used without cost to the model validation project and will also be deployed at RPU.
Ongoing Work

- PV Disaggregation
- Load disaggregation
- PV modeling using the dynamic response
- Extension of source impedance to voltage stability
Lessons learned in Connecting μPMUs

Sources of signal and noise

- physical system
- analog μPMU channel input
- μPMU data on device
- μPMU data in database
- μPMU data integrated to model

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

High accuracy device and logging
- 1% TVE, 0.02 magnitude

Total magnitude error for 1.42%
Operational Validation and Verification
Disaggregation of Behind the Meter PV

• Motivation
  – Highly distributed behind the meter PV is often invisible to operators
  – Estimated as a function of generation capacity and irradiance measurement
  – Individual communication from behind the meter inverters would be a solution – but reliant on customer communication networks

• Disaggregation of PV and Load gives visibility, on both the short term performance, and correlation of feeder conditions such as voltage profile

• Disaggregation allows resource to be used in operations, with greater confidence
  – Poor estimation of resource gives sub-optimal grid planning and operational conditions

• Outcome
  – Estimate real time (behind the meter) PV production downstream of μPMU measurement device
  – Using measured reactive power at substation and irradiance proxy to parameterize model – Model then runs in real time
  – Result in a 6% RMSE of installed capacity over all sky conditions

*patent pending