System Level Validation of Dynamics using PMU Data, Automated Tools, and Visualization

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# Acknowledgments and Thanks

- Work presented in these slides is based on the results of several projects including
  - BPA project TIP 357 with WSU (Techniques and Tools for System Level Validation of Transient Stability Models using PMU Data)
  - PSERC project S-60 (Load Model Complexity Analysis and Real-Time Load Tracking)

- Support is gratefully acknowledged!
  - Thanks also to-
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    - Katie Wood, Terry Doern, Kamshad Eshghi, Daniel Kuraspediani, and David Kleinschmidt at Bonneville Power Administration
    - Mani V. at WSU

Outline

- Background
- System Level Validation
  - Overall Process
  - Intermediate Steps
  - Starting Point Comparison
- Visualizations
- Equivanlencing
  - Region of Influence
- Sensitivity Analysis
  - Bus
  - Parameters
- GUI Prototype

Background

- Builds on recently concluded TIP 268
  - Developed methodology to verified commercial TS software packages against each other
  - Detected implementation differences, undocumented features, bugs
  - After cross-verifying models across packages, next logical step was to validate dynamic models with actual measurements
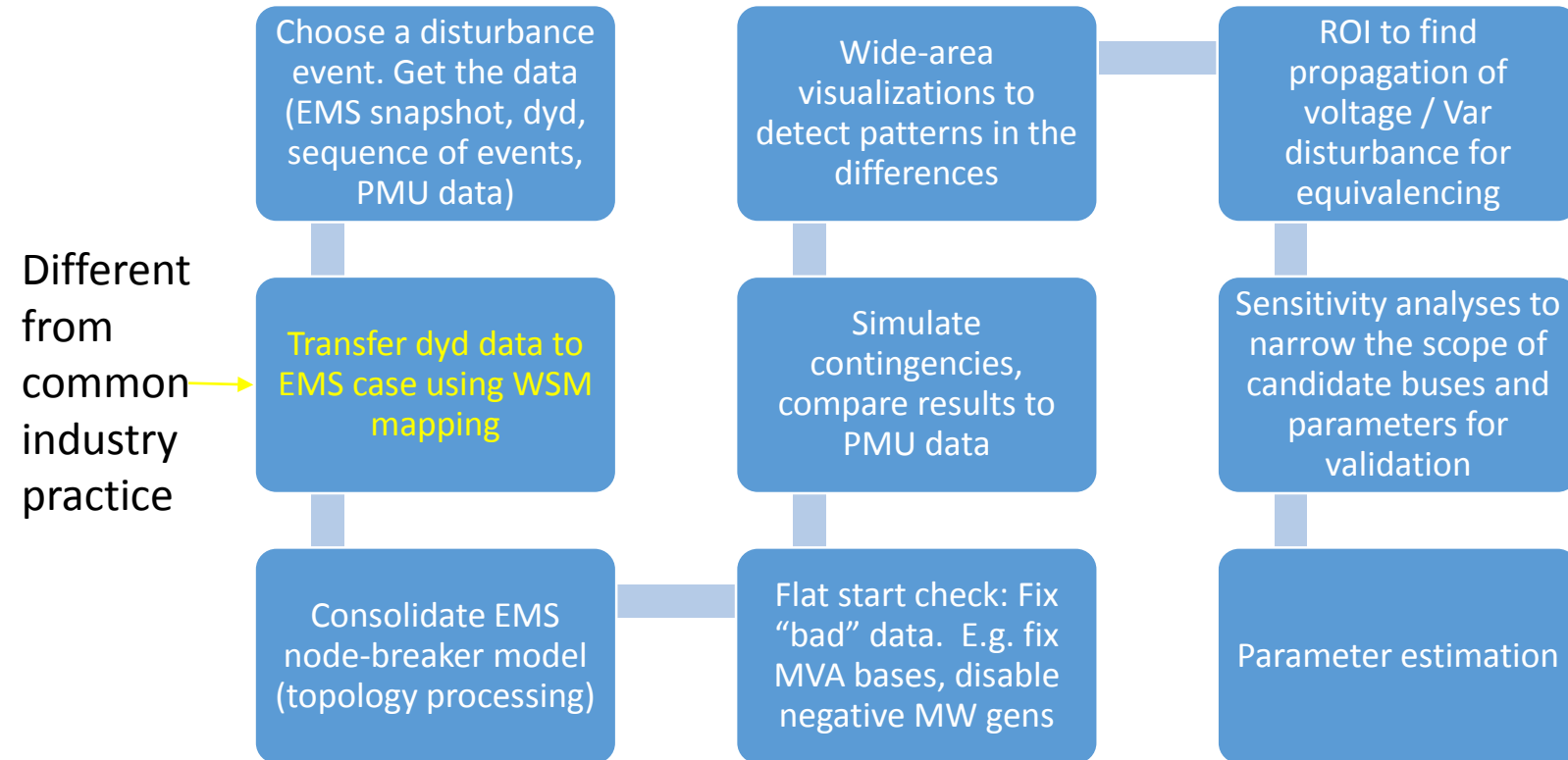
BEFORE

NOW
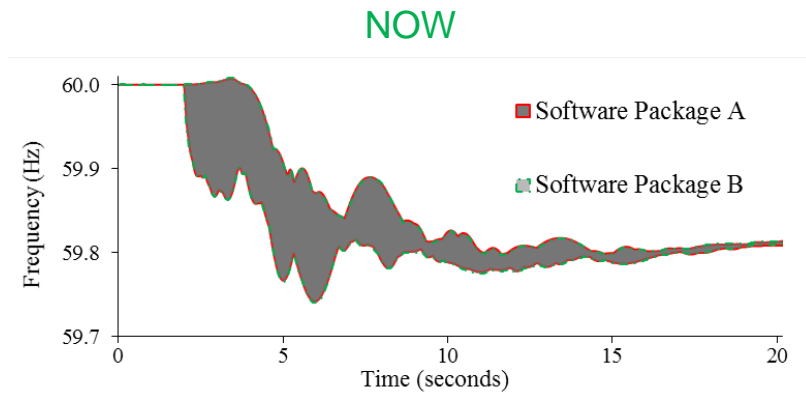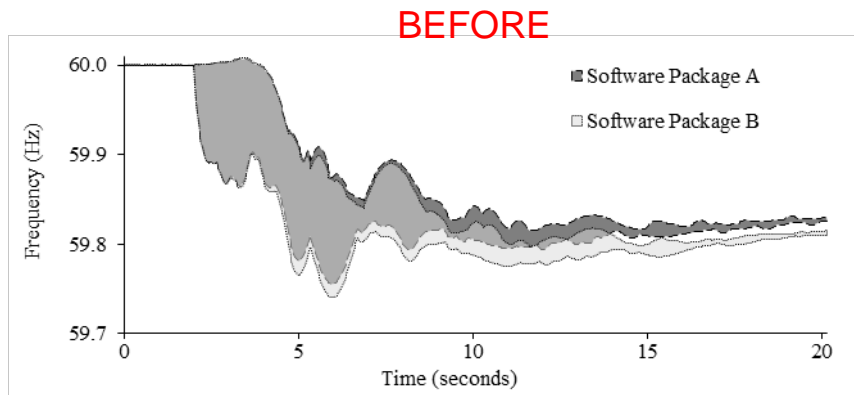
- Reference: K. S. Shetye, T. J. Overbye, S. Mohapatra, R. Xu, J. F. Gronquist and T. L. Doern, "Systematic Determination of Discrepancies Across Transient Stability Software Packages," in *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 432-441, Jan. 2016.

4

System Level Validation

- Using data from transmission system level (500 and 230 kV buses) PMU's
  - Voltage, frequency, flows
  - Not the typical generator or load point of interconnection (POI) validation
- Develop tools to automate validation process, and generalize it across events and cases
- Build on the vast body of work done in industry
- Focus is on load model validation
  - Challenges – load is constantly changing, needs frequent calibration, CMPLDW has 130+ parameters,
  - Automated tools should help
- Ongoing work – showing concepts, and preliminary results

Overall Validation Process

Choose a disturbance event. Get the data (EMS snapshot, dyd, sequence of events, PMU data)	Wide-area visualizations to detect patterns in the differences	ROI to find propagation of voltage / Var disturbance for equivalencing
Transfer dyd data to EMS case using WSM mapping	Simulate contingencies, compare results to PMU data	Sensitivity analyses to narrow the scope of candidate buses and parameters for validation
Consolidate EMS node-breaker model (topology processing)	Flat start check: Fix "bad" data. E.g. fix MVA bases, disable negative MW gens	Parameter estimation

Different from common industry practice →

Key throughout is to automate this process and build tools for the same

Other Intermediate Steps

- Modal Analysis
  - So far helpful in detecting source of oscillations seen in simulation results that do not exist in PMU data
  - Some renewable energy units tend to produce high frequency oscillations during the disturbance event. Due to their low output, these are disabled
- Mapping geo coordinate data: to make visualizations possible
  - A fourth of the EMS buses mapped so far, more in progress
- Lots of Simulation Automation!
  - PowerWorld Simulator as the engine, automated using PowerWorld SimAuto (COM Object based, can be used in conjunction with MATLAB, C#, VB, etc.)

# Starting Point Comparison*: WECC MVWG and UIUC results - Bus Malin

Image source: https://www.wecc.biz/Reliability/Model%20Validation%20Report%20for%20May%2016%202014%20RAS%20Event.pdf
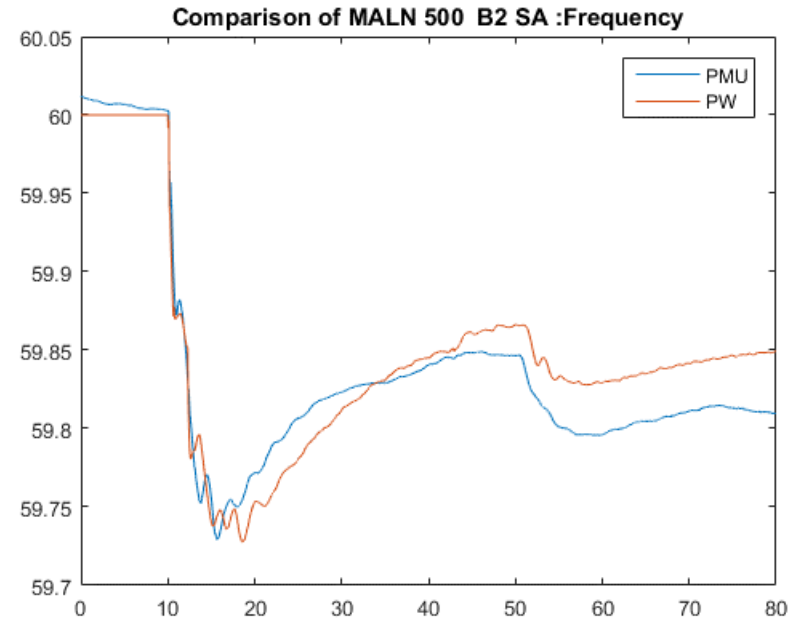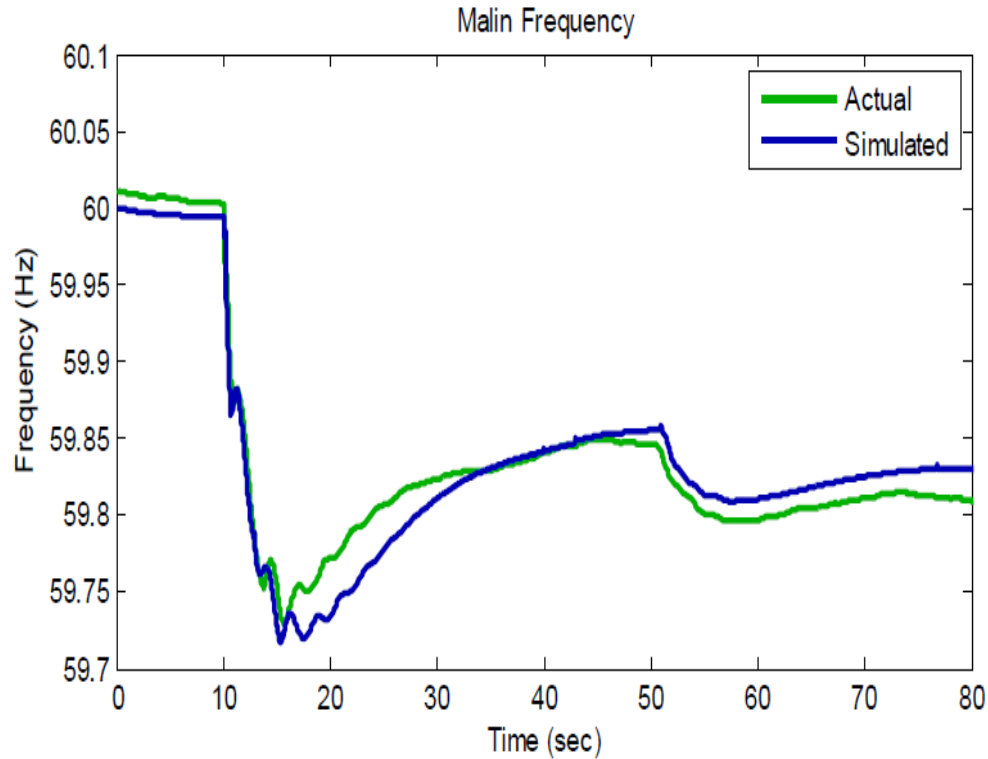
*Note: WECC results use planning case, with SE power flow conditions mapped to it. All gen and load dynamics data thus retained
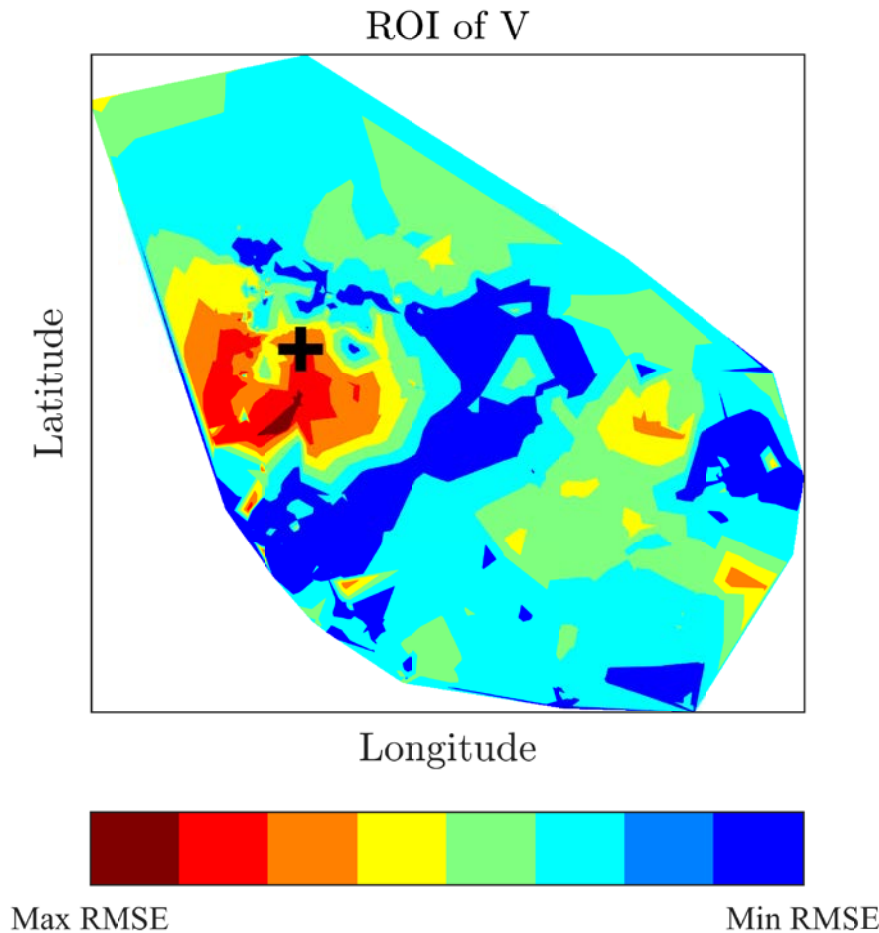
UIUC mapped gen dynamic data from planning to SE case. Load mapping hence dynamic data not available. MOTORW assumed for now . CMPLDW estimation and validation in progress.

Wide-Area Visualization of Voltage Deviations
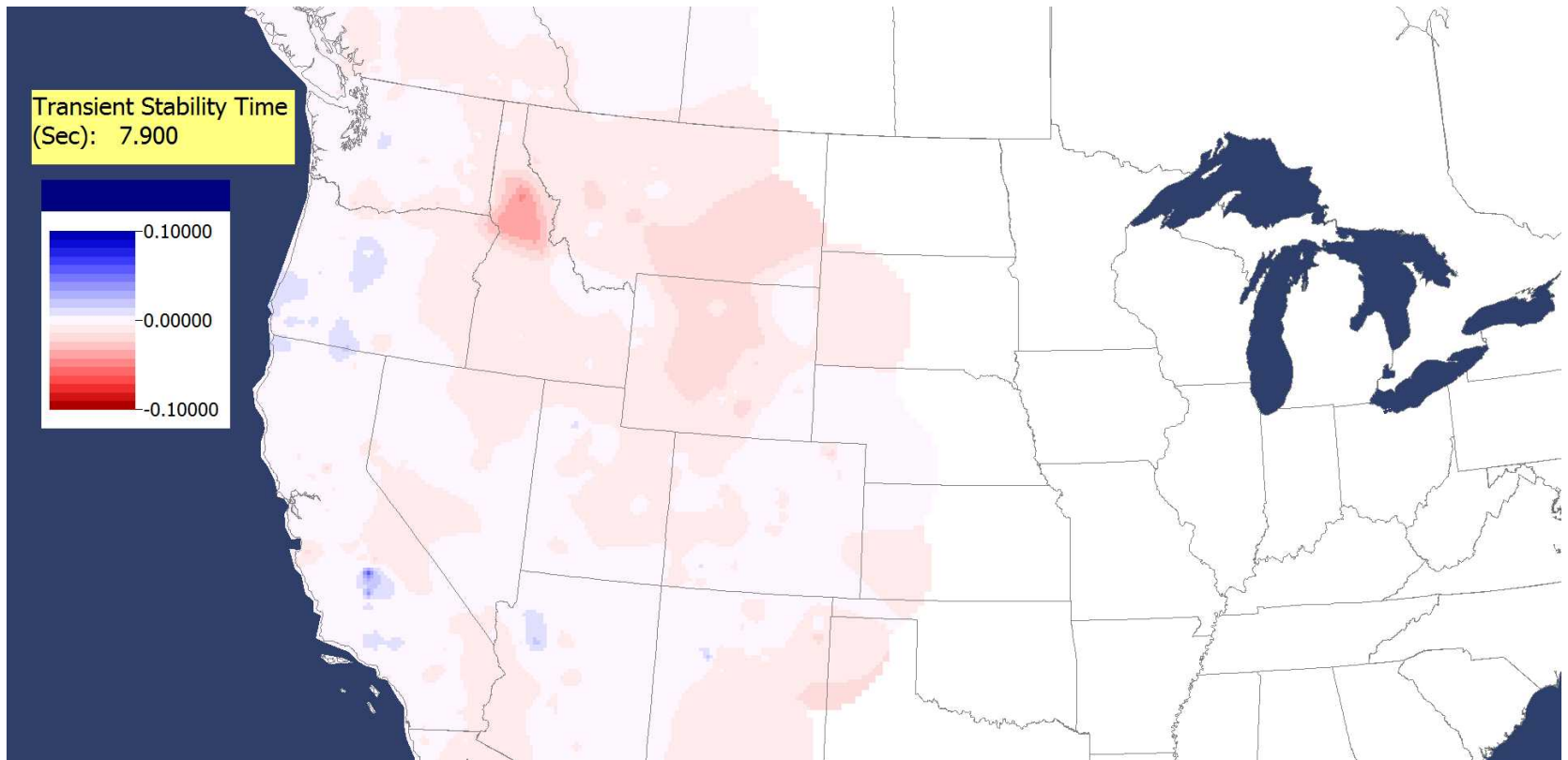
Region of Influence - Voltage

ROI of V

- Figure shows how far the simulated voltage disturbance propagates

- Calculated by taking the root mean square difference between the average of all bus voltages, and each bus voltage (in p.u.)

- Equivalent size selected by one or more color zones

Table shows % of buses in each color zone

COLOR	PERCENTAGE
Brown	0.3%
Red	6.6%
Orange 13.0%	
Yellow	19.1%
Green	36.1%
Cyan	71.9%
Light Blue	96.0%
Blue	100.0%

Region of Influence - Frequency

ROI of F
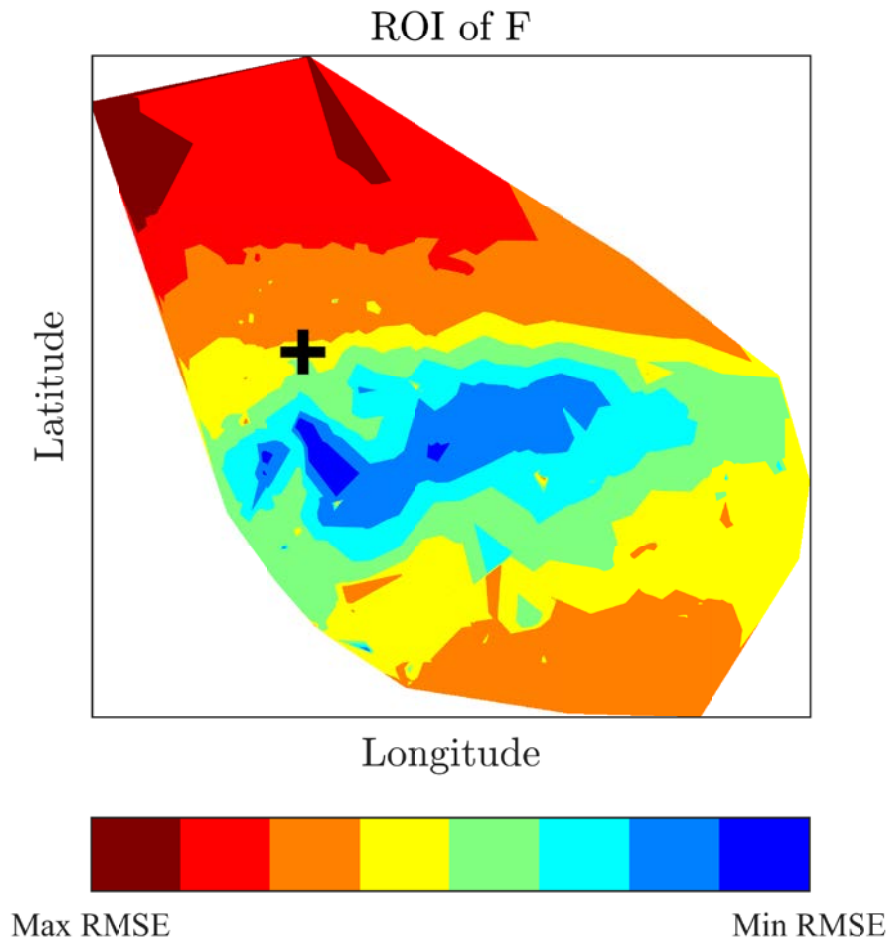
- Frequency is a global property; disturbance not localized

- ROI graph not intuitive

- System-wide "backbone" equivalent may need to be considered for this
  - Retain the high voltage (500 kV network) and some large generators and loads throughout WECC, equivalence the rest, emphasis on inertia equivalencing

Bus Sensitivities

- After reducing system size via equivalencing, can we further narrow down to the key (load) buses that are sensitive to this disturbance?

- Help in reducing # of loads and hence # of parameters in the estimation problem
  - 5305 load buses, 135 parameters each → 0.7 million parameters for estimation!! Intractable..

- Achieved through power injection based sensitivity analysis
  - For voltage, inject either 1 Mvar or a % (e.g. 10%) of the existing load at the bus, calculate RMSE at the PMU locations between the simulated voltages with and without the injection
  - Each injection simulation follows same sequence of events as original disturbance
  - Finally calculate sensitivity of each load bus; the ones with highest are good candidates for parameter sensitivity analysis and estimation

Load Model Parameter Sensitivities

- Once the most sensitive load buses have been determined, sensitivity analysis of parameters of the load models will be performed

- Focus will be on the CMPLDW

- Build on well-known existing methods such as trajectory sensitivity analysis

- Goal is to study both bus and load model sensitivities across multiple events to observe any commonalities among them, as well as characterizations by time of year, loading, location, etc.

Final Step: Parameter Estimation

- The last step is to solve the optimization problem of finding the most suitable values for the most sensitive parameters from the previous step

- Goal is to find feasible and meaningful values

- This Top-Down method (large system measurements to individual load parameters) of CMPLDW validation differs from how currently CMPLDW parameters are assigned in cases (bottom-up, i.e. thru components, and aggregations)

- Cross-validation of these two methods should make for an interesting analysis!

Tool GUI prototype

Unique Challenges: Bad Data

Detecting "bad" PMU data

• Sometimes models are reasonable but PMU's are "faulty"
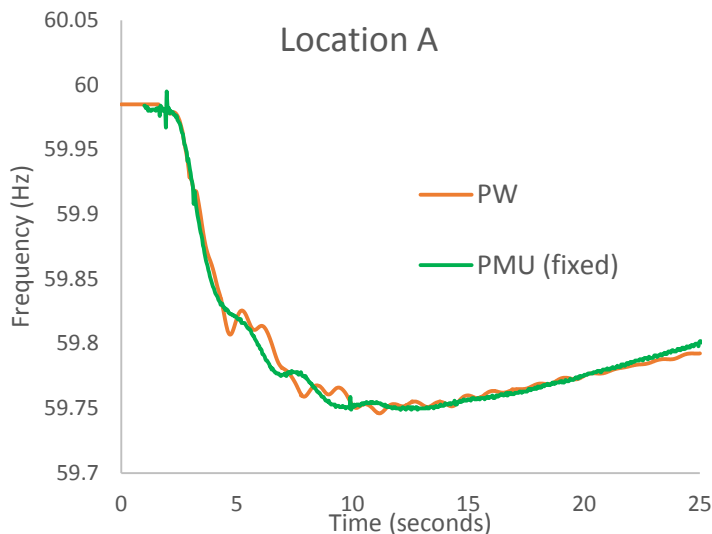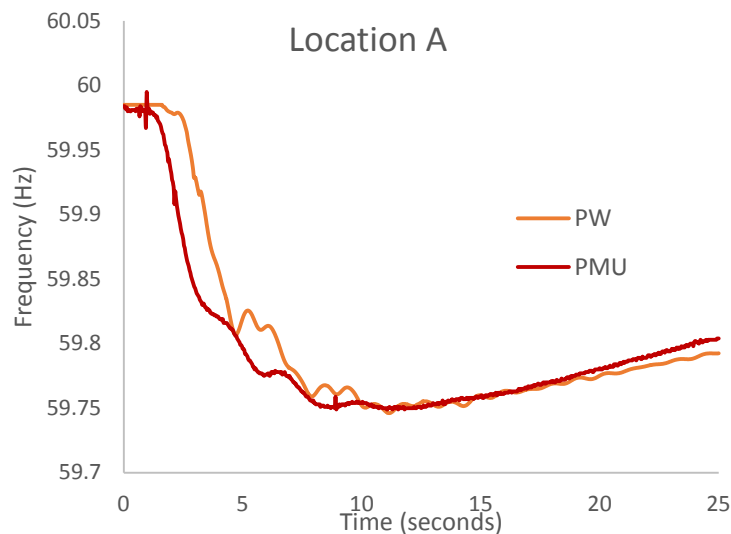
BPA Project Manager at the time confirmed that Location A (outside BPA) PMU had been time-tagged 1 second into the future. Figure on right shows PMU data shifted to show the correct time (green curve)

Ongoing / Future Work

- Work on backbone equivalents to model frequency disturbance propagation

- Validate equivalents (voltage ROIs and backbone) by comparing with full system simulations

- Parameter sensitivity analysis

- Test robustness of method across various events

Thank You! Questions?

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