CURENT
CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

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Real-Time Phasor-only State Estimator Applied to New England and New York Power Systems

Christoph Lackner, Joe H. Chow, Emily Fernandes (Rensselaer Polytechnic Institute)

Scott G. Ghiocel (Mitsubishi Electric Power Products, Inc.)

Russell Robertson, Ritchie Carroll (GPA)

Qiang Zhang, David B. Bertagnolli, Xiaochuan Luo (ISONE)

Daniel Ilse & De Tran (NYISO)

George Stefopoulos, Bruce Fardanesh, Alan Ettlinger, Saman Babaei (NYPA)

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Topics

- PMU data application research at RPI
- Phasor-only state estimation across power control regions
- Topology Processing
- Real Time Implementation on OpenPDC
- Results of Real Time Implementation in NE and NY Region

RT-PSE

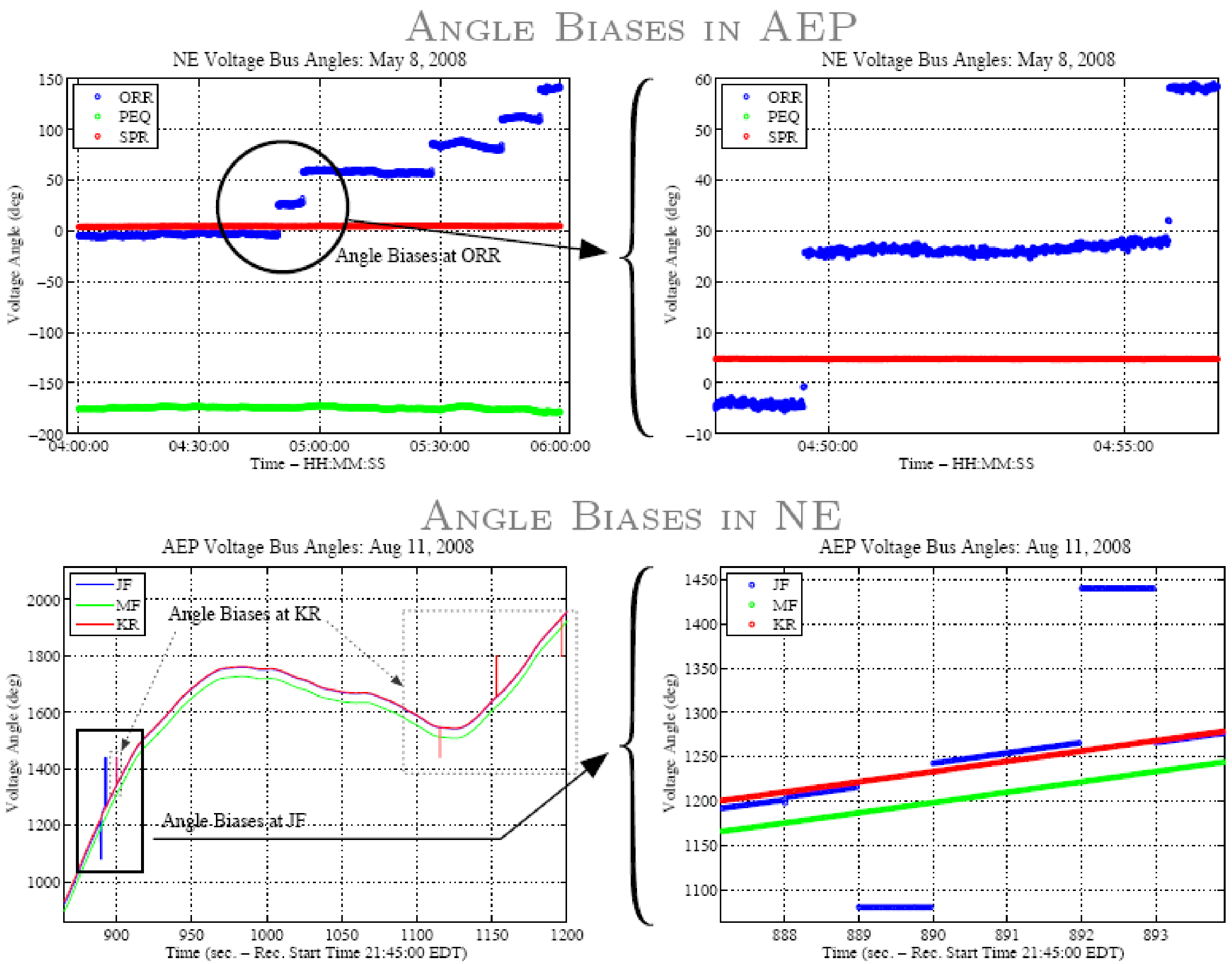
- NSF project to implement a real time phasor-only state estimator with Grid Protection Alliance (GPA) for New York (excluding NYC and Long Island) and New England 765/345/230 kV systems: from Western NY (Niagara Falls) to Eastern Maine
  - Connect NY and NE as a single SE – possible as NY and NE have PMUs "looking at" buses in the other system
  - The angle bias correction feature is critical – there are close-by buses with angle differences of the order of 0.08 degree.
  - Based on PMU data provided by NYISO and ISO-NE, the total vector error (TVE) between the corrected raw voltage data and the PSE voltage solution is normally less than 1%
- Implemented as an action adaptor on the GPA's OpenPDC for real-time operation.

Phase Angle Errors in PMU Data

- RPI has worked with phasor data from many PMUs (including some older models):
  - Voltage magnitude data are quite accurate (~1% error); current magnitude data less accurate
  - Voltage and current phase angle errors occur in some PMUs
    - “Random” jumps of 7.5 degrees or integer multiples of it, followed by resets at a later time
    - Slew/ramp with periodic resets
- Errors can be attributed to
  - Wrong phase connection to a PMU: a constant bias, trivial to correct
  - Signal processing algorithms used in the PMU: off-nominal frequency values and phase-locked loop implementation
  - Error with time synchronization: GPS clock signal overload or temporary loss of GPS signal
  - Delays due to instrumentation cables and filter time constants

Phase Errors Observed in PMU Data

Persistent, random, and drift errors in PMU phase data

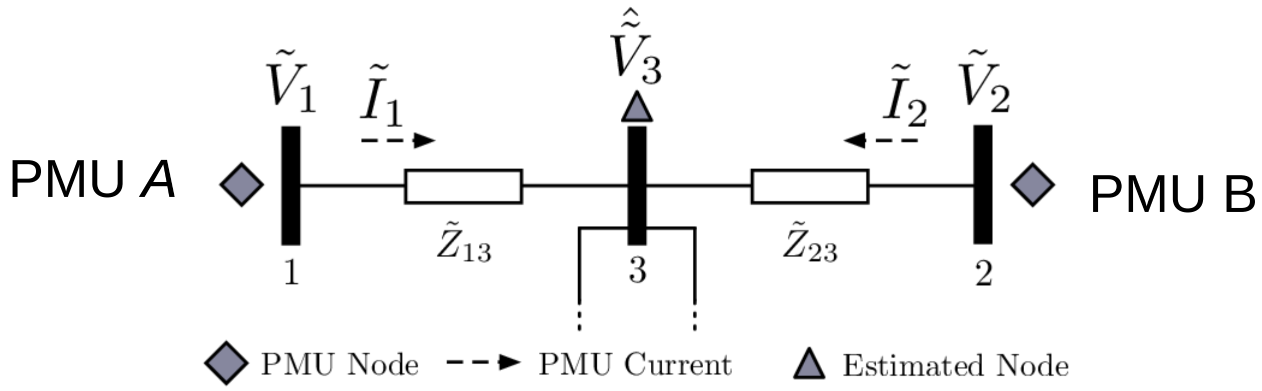


PSE with Phase Angle Bias Correction

- In the RPI PSE, in addition to the bus voltage magnitude and angle as unknowns, all except one PMU (reference) can incorporate a (fixed) angle bias correction factor, provided that there is a sufficient number of PMUs
- This PSE is nonlinear, but still is a least-squares problem with the Jacobian changing after each iteration
- This nonlinear PSE can also handle tap estimation and current scaling estimation
- The critical concept is a *redundant* bus defined as a bus whose voltage phasor can be computed from more than one PMU data set

Phase Angle Bias – Equations

Bus 3 is a redundant bus



PMU *A* at Bus 1

Voltage Angle →

$$\theta_1 - \theta_1^{\text{meas}} + \phi_A = e_{\theta_1}$$

Current Angles:

$$\delta_{13} - \delta_{13}^{\text{meas}} + \phi_A = e_{\delta_{13}}$$

$$\vdots$$

$$\delta_{1n} - \delta_{1n}^{\text{meas}} + \phi_A = e_{\delta_{1n}}$$

Same angle bias variable ϕ_A for all PMU channels

PMU *B* at Bus 2

$$\theta_2 - \theta_2^{\text{meas}} + \phi_B = e_{\theta_2}$$

$$\delta_{23} - \delta_{23}^{\text{meas}} + \phi_B = e_{\delta_{23}}$$

$$\vdots$$

$$\delta_{2k} - \delta_{2k}^{\text{meas}} + \phi_B = e_{\delta_{2k}}$$

Maximum-Likelihood Estimator (MLE)

- Measurements (*z*): voltage and current phasors
- States (*x*): voltage phasors
- Weighted least-squares:

$$\begin{aligned} \min \quad & \sum W_i e_i^2 \\ \text{subj. to} \quad & e_i = z_i - h_i(x) \quad \forall i \in \mathrm{M} \end{aligned}$$

- Minimize the error (*e*) between the measurements and the network model calculated values, *h*(*x*):

Voltage measurements: $\tilde{V}_i^{\text{meas}} = \tilde{V}_i + e_{\tilde{V}}$

Current measurements: $\tilde{I}_{ik}^{\text{meas}} = \dfrac{1}{R_{ik} + jX_{ik}}\left(\tilde{V}_i - \tilde{V}_k\right) + \dfrac{1}{2} jB_{ik}\tilde{V}_i + e_{\tilde{I}}$

- Can be implemented in rectangular or (better for the RPI PSE) polar coordinates

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PSE Solution Method

- Gauss-Newton iteration: solve for $\begin{bmatrix} \Delta x \\ \Delta \alpha \end{bmatrix}$ ← states (voltage phasors) ← parameters (bias, scaling, line parameters)

$$WH \begin{bmatrix} \Delta x \\ \Delta \alpha \end{bmatrix} = We$$

- Weight matrix W is the inverse of the covariance matrix
- Measurement Jacobian matrix H must be nonsingular:

$$2N_V + 2N_I \geq 2N_B + N_\alpha$$

  - In other words, the measurements must provide enough information to estimate the states and parameters
  - An ill-conditioned H indicates insufficient information

PSE Results by Linking 2 Control Areas

- Two control areas: New York and New England
  - NY has 21 PMUs (on 345 and 230 kV buses) and NE has 35 PMUs
  - There is a tie-line between these two areas with PMU voltage measurements on both buses and a PMU current measurement, thus the two control areas form one redundant cluster
  - The flow on a second tie-line (no PMU measurements) can be calculated from the PSE solution
- Angle Bias
  - Area 1: phase *a* is positive-sequence reference; Area 2: phase *b* is positive-sequence reference; the PSE successfully found the 120 degree phase shift, as part of the angle bias
  - After the 120 degree phase shift is accounted for, the angle bias is, in general, small: less than 1 degree.

PSE Results by Linking 2 Control Areas

- Total number of PMU voltages
  - 56 voltage measurements on substations directly from PMUs
  - 70 virtual PMU voltage measurements computed
  - Total of 126 buses observable
- Applications of real and virtual PMU measurements
  - Virtual generator PMU voltage and current measurements: importance of accurate PMU measurements – the angle across a line connected to a generator is less than 0.1 degree
  - Virtual wind turbine-generator PMU voltage and current measurements – study of reactive power control performance, and if wind data is available, study of active power control
  - Interface flow between the two areas during major disturbances
  - STATCOM PMU voltage and current output – study of voltage regulation characteristics

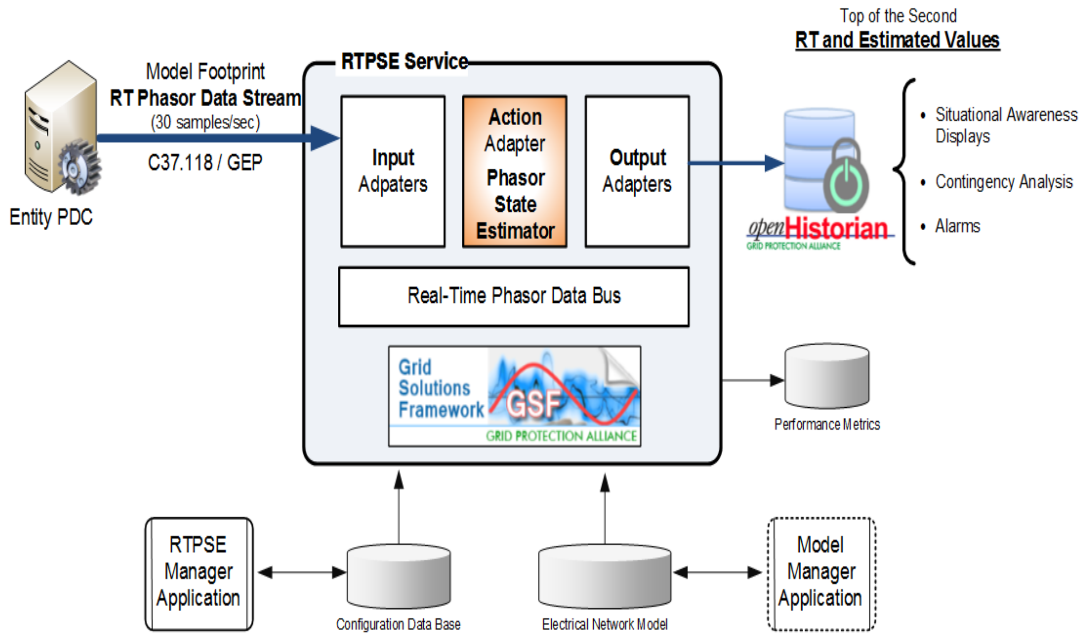
Topology Processor

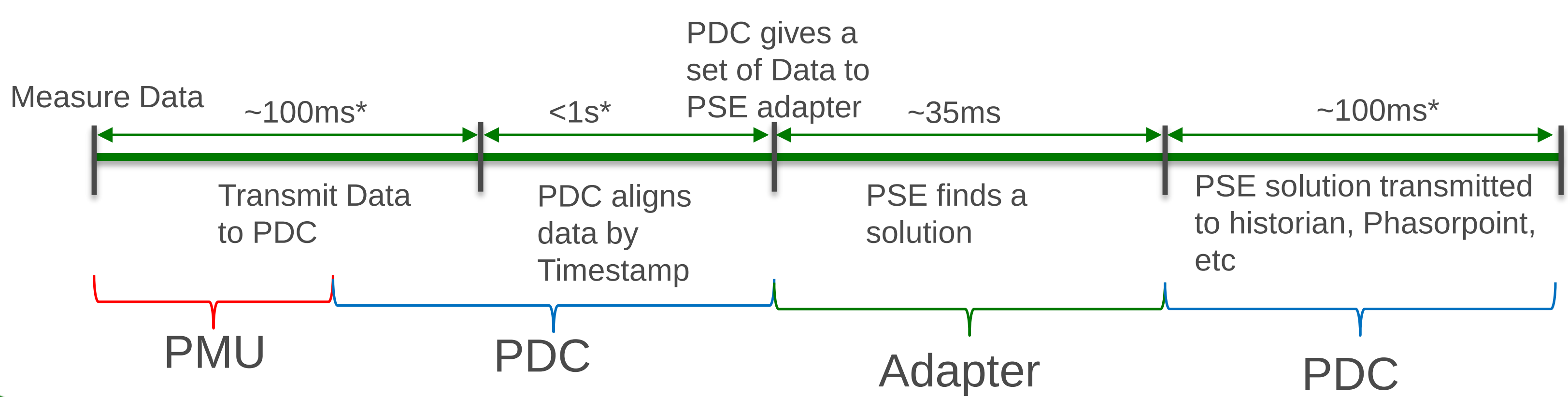
- Phasor observable Area changes
  - Line Outage
  - Loss of PMU data
- Determine Largest Phasor Observable Area
  - Redundant Cluster Algorithm
    - Necessary and sufficient network property for correction factors
    - Based on Spanning Tree Algorithm
  - Repeats every second to ensure a PSE solution can be found

PSE- RT Implementation

- PSE implemented as OpenPDC Adapter
  - Runs on GPA OpenPDC
  - Allows any PDC to provide Phasor Data
  - Can send solution to any other PDC (IEEE 37.118)
- Provides a solution in 30ms
  - PSE solution for every PMU measurement
- Solution includes a set of correction factors where applicable
  - angle bias
  - current magnitude
  - Tap estimation

RT-PSE Service Concept





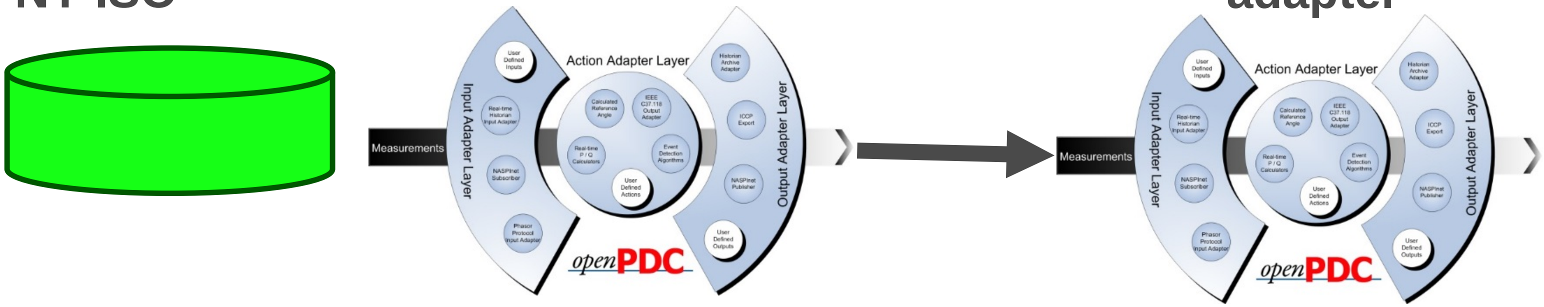
* Network delays change significantly depending on Network conditions

RPI RT Testing Setup

CSV PMU Data provided by ISO-NE and NY-ISO

Open PDC Server to simulate ISO PDC

Open PDC running PSE adapter



- Test system runs at RT speeds
  - Provides 30 measurements per second
  - PSE solution provided 30 times a second
- Runs real 5 minute data sets
  - NE network and data provided by ISO-NE
  - NY network and data provided by NY-ISO

Result ISO-NE and NYISO General Performance

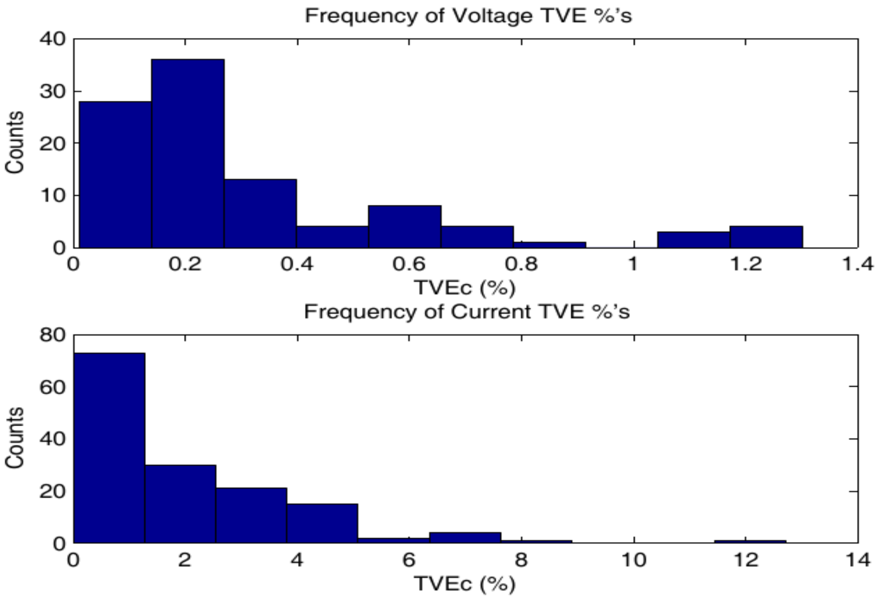
- 56 PMU Buses
  - 128 Voltage Measurements
  - 201 Current Measurements
- Topology
  - 126 Observable Buses
  - 73 Redundant Buses
  - 70 Virtual PMU Buses
- Increased “visible” PMU data from 56 to 126 Buses

Result ISO-NE and NYISO Accuracy

- Average corrected TVE

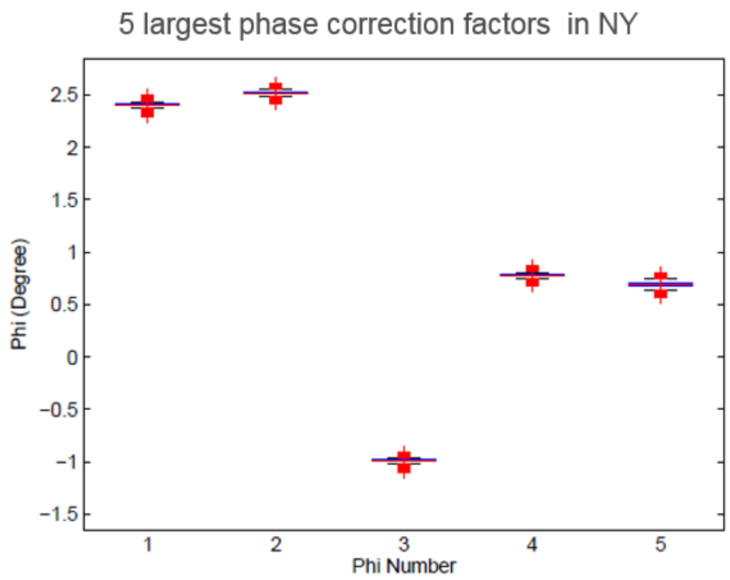
TVEc (%)	Mean	Max	Standard Deviation
Voltage	0.3223	1.3029	0.2988
Current	1.9644	12.7404	1.9138

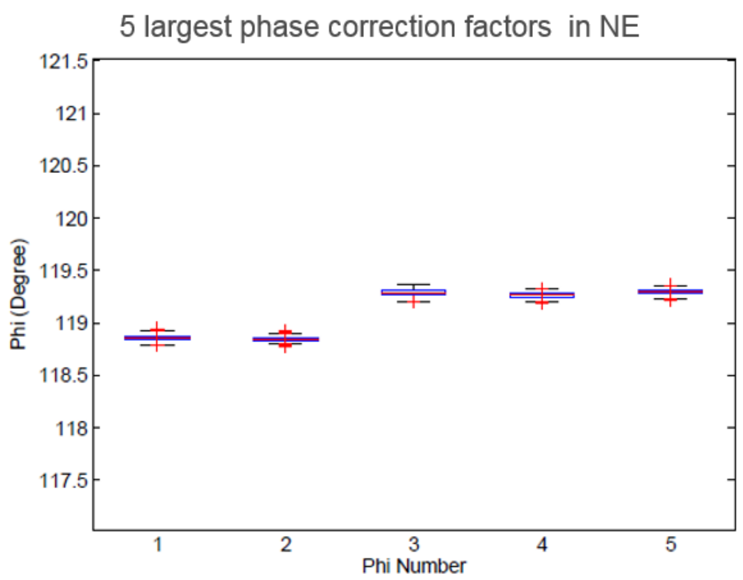
- Corrected TVE histograms



Result ISO-NE and NYISO Consistency of solution

- Estimated correction factors are intended to account for <u>constant</u> error in the field.
- Therefore correction factors should have relatively small variation over time





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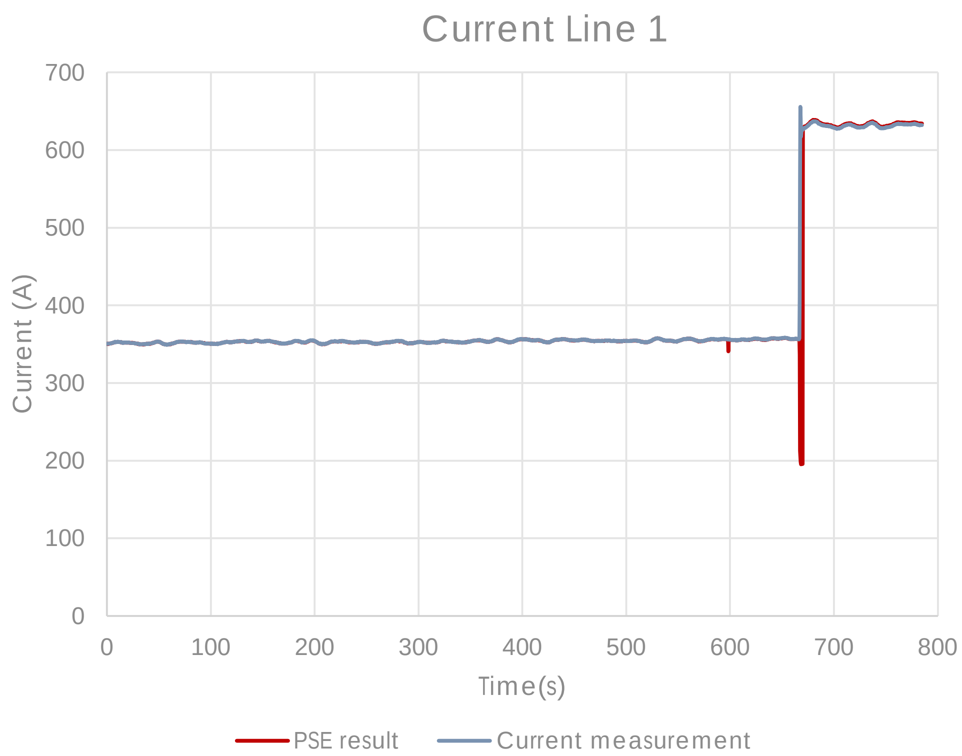
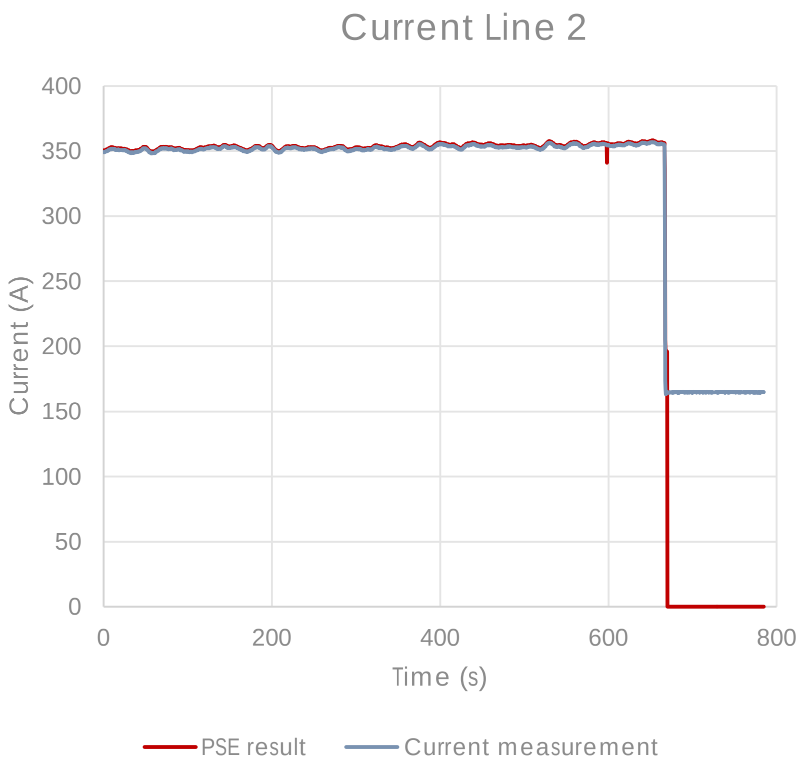
Result NE System

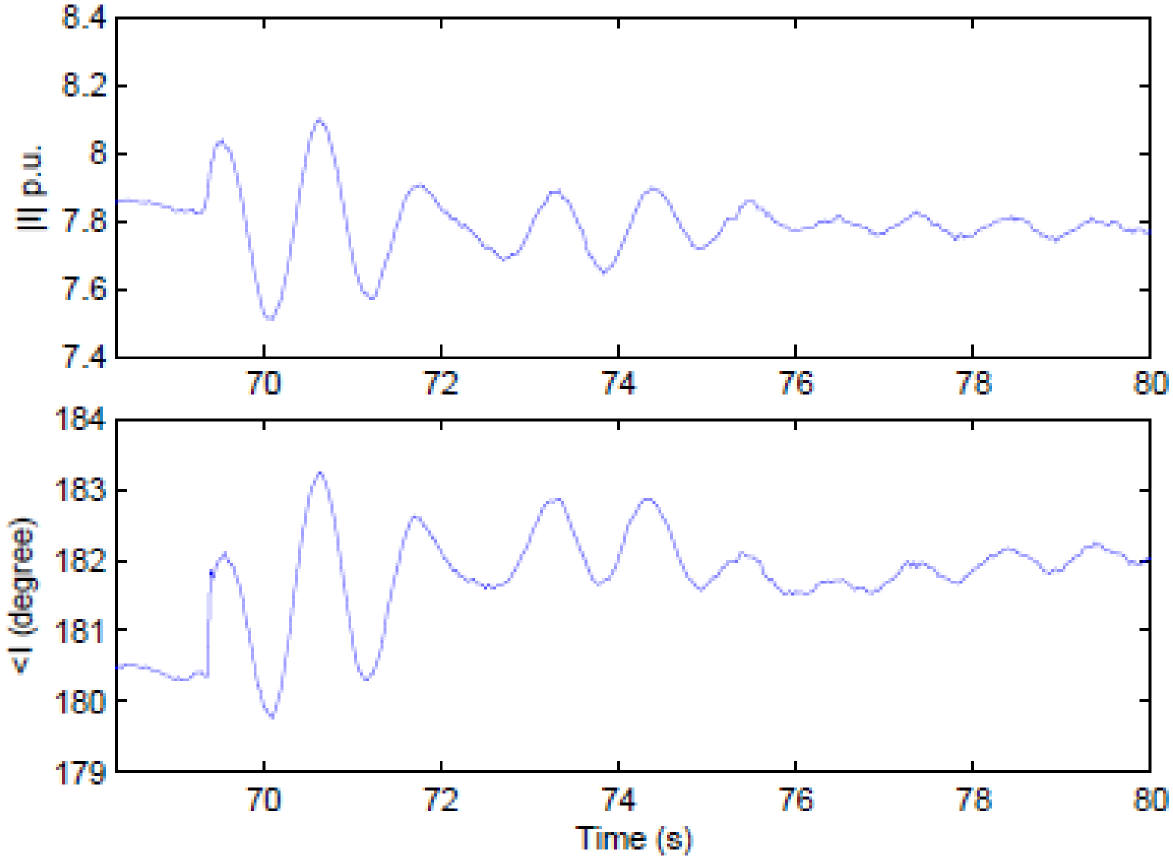




Currents for 2 parallel Lines.

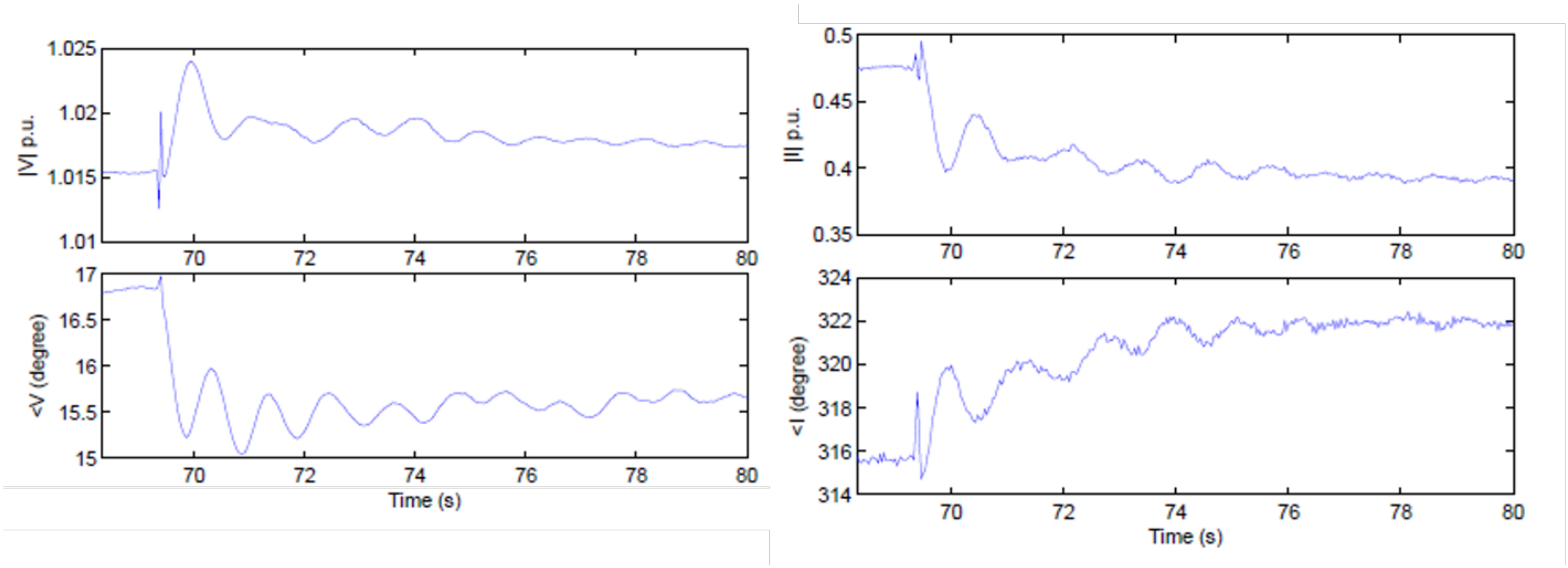
- Line 2 is taken offline, but the measured current includes a variable Reactor.
- Topology Processor recognized Line 2 as out and adjusted Phasor Observable Area

Result NY System



Generator Output (Current Phasor) during a Generator trip in Ontario

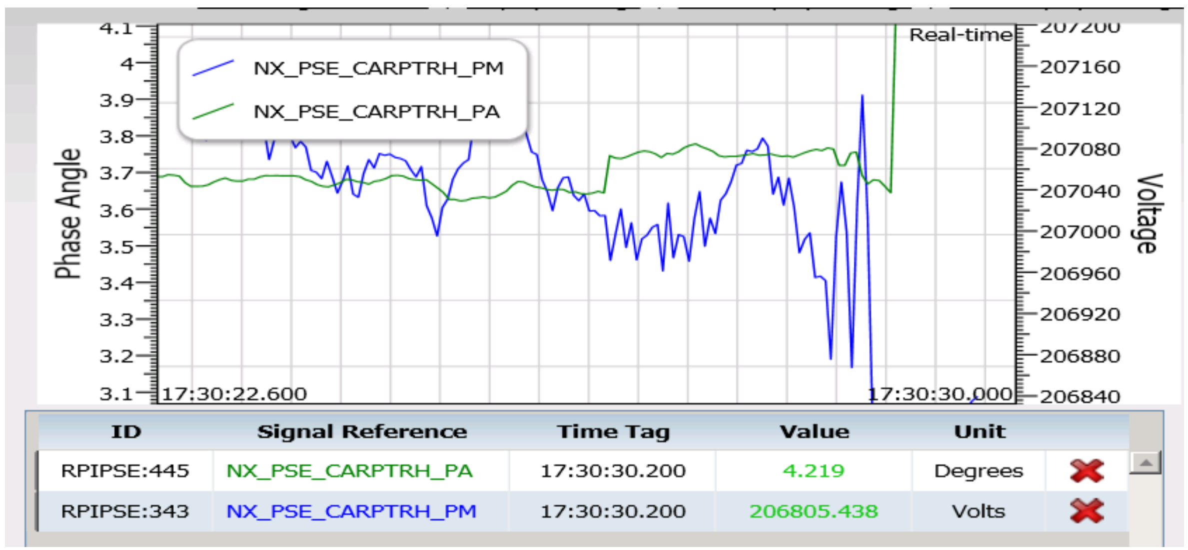
Result NY System

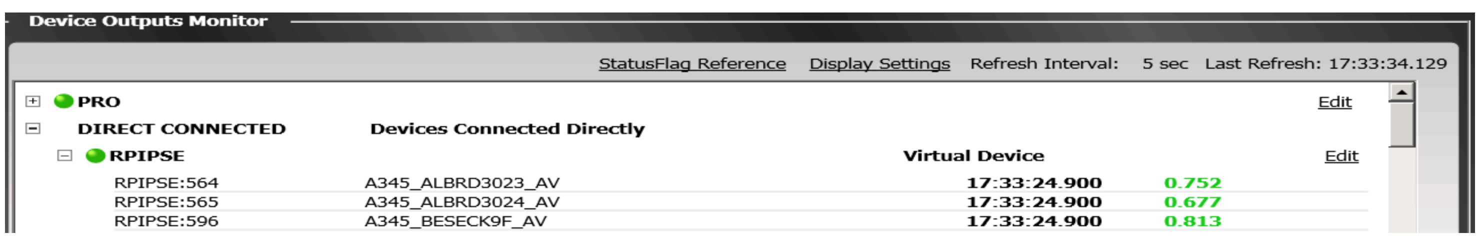


Wind Hub Current and Voltage Phasor during a Generator trip in Ontario

RT demonstration ISO-NE

- Currently runs on live PMU data at ISO-NE
  - Measurements for 60 Buses
  - 24 virtual buses
  - Average State estimator error: 0.005





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