Visions of Synchrophasor Pioneers: A Technical Symposium in Honor of Professors Arun Phadke and James Thorp

Phasor State Estimator: Data Quality Enhancement and Wide-Area System Monitoring

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Synchrophasors for State Estimation

• 1985 and 1986 Power System Transactions papers by Phadke, Thorp, and Karimi – first papers on state estimation using synchrophasor data

• Early approach is to add PMU data to SCADA estimator
  – NYPA SE implementation in the 1990/2000
  – A NASPI project undertaken with TVA, Entergy, and Alstrom
  – Prof. Ali Abur has shown the benefit of having PMU data to improve the convergence of SE solutions

• Three-phase tracking state estimator – Dominion and Virginia Tech

• With more PMUs installed, it becomes possible to develop a state estimator using PMU data only.
Phasor State Estimator Concept

• What is a phasor state estimator (PSE)?
  – A state estimator performed at 30 samples per second, using only synchrophasor measurements of bus voltages and line currents
  – Intended for high-voltage buses: 765/345/230 kV

• Why use PSE?
  – Calculate “pseudo” PMU measurements at unmeasured buses and lines
  – Correlate PMU data across a network, allowing data quality enhancement and filling in missing data
  – Enable interface flow calculation even though not all flows are directly measured with PMUs
  – Monitor generator (fossil and wind turbine) active and reactive power outputs without having a PMU at the generator substation
  – High-sampling-rate allows visibility of disturbances (voltages and power flows), disturbance propagation, voltage stability, frequency response, and oscillations
Phasor State Estimator Concept

• What is needed for a PSE?
  – Good PMU coverage of the high-voltage buses
    • One-third coverage for observability
    • One-half coverage for cross validation (NY and NE)
  – Network data (same as SCADA SE) but no load values required
  – A least-squares algorithm with ability to correct for scaling errors and phase biases (formulation using voltage magnitude and phase)
  – No differential equations required (c.f. dynamic state estimation)
  – For real-time operation: launched from a PDC

• Other potentials with PSE:
  – Cross-regional SE for stability and vulnerability monitoring: a PSE across MISO-PJM-NY-NE
  – Within a control region, a hierarchical SE with PSE as anchored values for the higher voltage buses, and a non-iterative state calculator for the lower voltage buses
PSE for Central NY

- 6 PMUs in 6 substations
- 13-bus observable network (one-third of NY by area)
- Covers critical power transfer interfaces
- Some interface flows are unmeasured (dashed lines)
- PSE calculates missing flows and enables interface monitoring
Phasor State Estimation

• Objective of PSE:
  – Find the best-fitting solution for the network model given a set of phasor measurements

• Why use synchrophasors only?
  – RTUs report data every few seconds
  – Conventional state estimator (SE) takes the latest value

<table>
<thead>
<tr>
<th></th>
<th>Conventional SCADA</th>
<th>Synchrophasors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reporting Rate</td>
<td>Once every few seconds</td>
<td>30+ samples/sec</td>
</tr>
<tr>
<td>State Estimation</td>
<td>No time-alignment</td>
<td>Time-aligned</td>
</tr>
<tr>
<td>System Dynamics</td>
<td>Not visible</td>
<td>Visible to operators</td>
</tr>
</tbody>
</table>

Goal: Wide-area coverage of the high-voltage transmission system.
PMUs Enable Dynamic Visibility

Comparison of SCADA vs. PMU data for a loss-of-generation event
**Maximum-Likelihood Estimator (MLE)**

- **Measurements** ($z$): voltage and current phasors
- **States** ($x$): voltage phasors
- **Weighted least-squares:**
  \[
  \min \sum W_i e_i^2
  \]
  subj. to
  \[
  e_i = z_i - h_i(x) \quad \forall i \in M
  \]
- **Minimize the error** ($e$) between the measurements and the network model, $h(x)$:
  
  **Voltage measurements:**
  \[
  \tilde{V}_i^{\text{meas}} = \tilde{V}_i + e_{\tilde{V}}
  \]

  **Current measurements:**
  \[
  \tilde{I}_{ik}^{\text{meas}} = \frac{1}{R_{ik} + jX_{ik}} (\tilde{V}_i - \tilde{V}_k) + \frac{1}{2} jB_{ik} \tilde{V}_i + e_{\tilde{I}}
  \]
- **Can be implemented in rectangular or polar coordinates**
Phase Angle Bias

• Relative phase angle bias can be caused by:
  – Timing error
  – Phasor calculation (frequency estimator algorithm)

• All channels of a PMU share the same timing circuitry and phasor calculation algorithms

• Approach: Estimate the phase angle bias by introducing a new variable in the measurement equations
Phase Angle Bias – Equations

PMU A at Bus 1

\[
\begin{align*}
\theta_1 - \theta_1^{\text{meas}} + \phi_A &= e_{\theta_1} \\
\delta_{13} - \delta_{13}^{\text{meas}} + \phi_A &= e_{\delta_{13}} \\
\vdots \\
\delta_{1n} - \delta_{1n}^{\text{meas}} + \phi_A &= e_{\delta_{1n}}
\end{align*}
\]

PMU B at Bus 2

\[
\begin{align*}
\theta_2 - \theta_2^{\text{meas}} + \phi_B &= e_{\theta_2} \\
\delta_{23} - \delta_{23}^{\text{meas}} + \phi_B &= e_{\delta_{23}} \\
\vdots \\
\delta_{2k} - \delta_{2k}^{\text{meas}} + \phi_B &= e_{\delta_{2k}}
\end{align*}
\]

Same angle bias variable \( \phi_A \) for all PMU channels

Voltage Angle

Current Angles

PMU Node ——> PMU Current

Estimated Node

PMU A

PMU B

Voltage

Angles

\[ \tilde{V}_1 \]

\[ \tilde{I}_1 \]

\[ \tilde{V}_3 \]

\[ \tilde{I}_2 \]

\[ \tilde{V}_2 \]

\[ \tilde{Z}_{13} \]

\[ \tilde{Z}_{23} \]
Phase Angle Bias – Example

- Two multi-channel PMUs at one substation
- Measured voltage phase angles have a 0.25° difference
Current Scaling Factors

• Unlike voltage phasor measurements:
  – Current flows have a wide range of values
  – No simple “sanity check” (e.g., 0.95-1.05 p.u.)

• Bad scaling is harder to detect in current phasors than voltage phasors
  – More easily detected by correlating measurements from different substations

• **Approach:** Estimate the scaling error using a new variable in the current measurement equations
Current Scaling Factors – Equations

PMU A at Bus 1

\[
(1 + c_{13}) I_{13} - I_{13}^{\text{meas}} = e_{I_{13}}
\]

\[
(1 + c_{1n}) I_{1n} - I_{1n}^{\text{meas}} = e_{I_{1n}}
\]

Independent scaling for each current channel

PMU B at Bus 2

\[
I_{23} - I_{23}^{\text{meas}} = e_{I_{23}}
\]

\[
(1 + c_{2k}) I_{2k} - I_{2k}^{\text{meas}} = e_{I_{2k}}
\]

Current Magnitudes

Independent estimates of $\tilde{V}_3$ should agree.
Disturbance Events

• Examine 20 sec window of data including disturbance
  – Disturbances occur around 2 sec
  – PSE solution calculated for each time sample (30/sec)

• Interface monitoring for real events:
  – Power flow
  – Angle separation

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event 1</td>
<td>Loss-of-generation to the East (500 MW)</td>
</tr>
<tr>
<td>Event 2</td>
<td>Loss-of-generation to the East (800 MW)</td>
</tr>
<tr>
<td>Event 3</td>
<td>Loss-of-generation to the East (700 MW)</td>
</tr>
<tr>
<td>Event 4</td>
<td>Loss-of-generation to the West (800 MW)</td>
</tr>
<tr>
<td>Event 5</td>
<td>Loss-of-generation to the East (No PMU data from Bus 5)</td>
</tr>
<tr>
<td>Event 6</td>
<td>Tap changing (to demonstrate tap ratio estimation)</td>
</tr>
</tbody>
</table>
## Estimated Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{\text{ref}} = 0$</td>
<td>PMU 1A (at Bus 1) is the reference for angle bias</td>
</tr>
<tr>
<td>$\phi_1$</td>
<td>Angle bias for PMU 1B (at Bus 1)</td>
</tr>
<tr>
<td>$\phi_4$</td>
<td>Angle bias for PMU 4 (at Bus 4)</td>
</tr>
<tr>
<td>$\phi_5$</td>
<td>Angle bias for PMU 5 (at Bus 5)</td>
</tr>
<tr>
<td>$\phi_{10}$</td>
<td>Angle bias for PMU 10 (at Bus 10)</td>
</tr>
<tr>
<td>$\phi_{11}$</td>
<td>Angle bias for PMU 11 (covers Buses 11 and 12)</td>
</tr>
<tr>
<td>$c_{46}$</td>
<td>Scaling correction for current measurement $I_{46}$</td>
</tr>
<tr>
<td>$c_{45}$</td>
<td>Scaling correction for current measurement $I_{45}$</td>
</tr>
<tr>
<td>$X_{45}$</td>
<td>Series reactance for Line 4–5</td>
</tr>
<tr>
<td>$B_{45}$</td>
<td>Shunt susceptance for Line 4–5</td>
</tr>
<tr>
<td>$a_{1-10,1}$</td>
<td>Transformer tap ratio on Branch 1–10, Circuit 1</td>
</tr>
<tr>
<td>$a_{1-10,2}$</td>
<td>Transformer tap ratio on Branch 1–10, Circuit 2</td>
</tr>
<tr>
<td>$a_{11-12}$</td>
<td>Transformer tap ratio on Branch 11–12</td>
</tr>
</tbody>
</table>
Central NY System

Legend

- Green circle: Measured Bus Voltage (PMU Location)
- Orange circle: Estimated Bus Voltage
- Blue circle: Observable Bus Voltage
- Green line: Measured Line Current (1 direction)
- Blue line: Measured Line Current (both directions)
- Black dashed line: Unmeasured (calculated) Line Current

Interface to external system

Stability interfaces

To load center
Angle Bias – PMUs 4 & 5
Estimated Current Scaling Factors

![Diagram showing estimated current scaling factors for different events labeled as $c_{46}$ and $c_{45}$ for various events 1 to 5.](image-url)
Transformer Tap Ratio Estimation

![Graph showing transformer tap ratio estimation over time. The graph plots tap ratio against time (in seconds) with two curves labeled $a_{1-10,1}$ and $a_{1-10,2}$. The tap ratio values range from 1.01 to 1.04.](image-url)
Data Quality Enhancement

• Calculate system-wide total vector error (TVE)
  – With real data, actual state values are unknown
  – Include current scaling factors to correct large errors
  – Assume PSE solution is correct

• Reduction of TVE across all PMUs (< 1%):

<table>
<thead>
<tr>
<th>Event</th>
<th>Current scaling correction only</th>
<th>Current scaling and angle bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean TVE</td>
<td>Mean TVE</td>
</tr>
<tr>
<td>Event 1</td>
<td>1.162%</td>
<td>0.890%</td>
</tr>
<tr>
<td>Event 2</td>
<td>1.106%</td>
<td>0.907%</td>
</tr>
<tr>
<td>Event 3</td>
<td>0.993%</td>
<td>0.701%</td>
</tr>
<tr>
<td>Event 4</td>
<td>1.051%</td>
<td>0.852%</td>
</tr>
</tbody>
</table>
Interface Monitoring for Central NY

- Use PSE to estimate unmeasured buses and flows
- Monitor interfaces in real time for disturbance events
Monitoring Transfer Interfaces – Event 2

\[ \Delta P \text{ (MW)} \]

\[ \Delta \theta_{1-9} \text{ (degrees)} \]

Time (sec)
Monitoring Transfer Interfaces – Event 4

\[ \Delta P \text{ (MW)} \]

\[ \Delta \theta_{1-9} \text{ (degrees)} \]

Time (sec)
Conclusions

• Data quality improvement by using current synchrophasors to correlate PMUs across the system
• Unmeasured voltage and current phasors (and thus interface flows) can be estimated if observable
• Estimation of angle biases, current scaling factors, and line parameters with sufficient redundancy
• PSE enables system monitoring for dynamic propagation of disturbances across transfer interfaces
• Interest in expanding the PSE to other parts of the NY power system and the New England power system: these two systems have close to 50% PMU coverage of their 345 kV substations.
Acknowledgements

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