Application of Synchrophasor Data to Power System Operations

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Synchronized Dynamic Measurements in USA

- Recent past: a few PMUs, mostly for oscillation analysis (WECC)
- Now: significantly larger number (1000+) of PMUs
- Future:
  - PMU on every HV transmission substation (China)
  - Micro-PMU on some distribution substations
  - Time-tagged measurements (not necessarily 3-phase) in power plants and other control equipment
PMU Data Application Development at RPI

• PMU data blocks as low-rank matrices
  – Data compression
  – Missing data recovery
  – Disturbance detection

• Phasor-only state estimator – under testing with 50+ PMUs and 120+ phasor observable buses

• Control equipment performance validation
## Space-Time View of PMU Data

<table>
<thead>
<tr>
<th>PMU channels</th>
<th>Time</th>
<th>PMU data points</th>
<th>Most recent data block</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Space</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NY PMUs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NE PMUs</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>PJM PMUs</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Other PMUs</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td><strong>Disturbance 1</strong></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td><strong>Disturbance 2</strong></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Disturbance 3</strong></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Real time</strong></td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
<td><img src="image19.png" alt="Image" /></td>
</tr>
</tbody>
</table>

- **Missing data**
- **Bad data**
- **Cyber attack**
PMU Data Quality Improvement

- Fill in missing data
- Correct bad data
- Alarm on disturbances
- Check on system oscillations
- Identify what kind of disturbances using disturbance characterization
- Figure out if there are any correlations between the disturbances and the possibility of cascading blackouts
- Detect cyber attacks – beyond the routine black-hole (blocking all data transmission) and gray-hole (blocking some data transmission) types of attacks

- Can all these tasks be done on a single platform? Single-channel processing will be hopeless.
PMU Block Data Analysis

- Power system is an interconnected network – data measured at various buses will be driven by some underlying system condition
- The system condition may change, but some consistent relationship between the PMU data from different nearby buses will always be there
- If one gets some PMU data values at time $t$ at a few buses, it may be to estimate what the PMU values at other nearby buses are.

![Fig. 7. Current magnitudes of PMU data (9 current phasors out of 37 phasors)](image1)

![Fig. 3. Original frequency profile](image2)
Low-Rank Power System Data Matrix

- Joint work with Prof. Meng Wang and many students at RPI
- Previous work by Dahal, King, and Madani 2012; Chen, Xie, and Kumar 2013
- Example: well-known Netflix Prize problem
Low-Rank Matrix Analysis for Block PMU Data

• Analyze PMU data at multiple time instants collectively from PMUs in electrically close regions and distinct control regions.

• Process *spatial-temporal blocks* of PMU data for
  – PMU data compression – singular value decomposition/principal component analysis: keep only significant singular values and vectors
  – Missing PMU data recovery – matrix completion using convex programming
  – Disturbance and bad data detection – when second and third singular values become large
  – Detection of PMU data substitution – sum of a low-rank matrix and a sparse matrix, using convex programming decomposition algorithm
Data Compression

• A matrix $L$ of multiple channel PMU data for a certain time period
• SVD: $L = U\Sigma V^T$
• If $L$ is low rank, it can be approximated by retaining only the largest singular values in $\Sigma$
  \[
  \hat{L} = \hat{U} \hat{\Sigma} \hat{V}^T
  \]
• Reduced storage using smaller number of singular vectors
• Reconstruct the data for each channel using the SVD formula
• Lossy compression
• Illustration: 6 frequency channels for 20 seconds ($L$ is 6x600) during a disturbance
• SVD of $L$
  \[
  L = [3597.1, 0.086, 0.022, 0.010, 0.0084, 0.0078]
  \]
Data Compression Example

From: Yu Xia
Missing Data Recovery Formulation

• Problem formulation: given part of the entries of a matrix, need to identify the remaining entries
• Assumption: the rank of the matrix is much less than its dimension
• Intuitive approach: among all the matrices that comply with the observations, search for the matrix with lowest rank
• Technical approach: reconstruct the missing values by solving an optimization problem: nuclear norm minimization (Fazel 2002, Candes and Recht 2009)
• Many good reconstruction algorithms are available using convex programming, e.g., Singular Value Thresholding (SVT) (Cai et al. 2010), Information Cascading Matrix Completion (ICMC) (Meka et al. 2009) – faster
Missing Data Example

- 6 PMUs, 37 channels, 30 sps, 20 sec data
Results: Temporally Correlated Erasures

- Characteristics: If a channel in a particular PMU is lost at a particular time, there is a probability that $\tau$ trailing data points will also be lost.

From: Pengzhi Gao, Meng Wang
Phasor-Data-Only State Estimation (PSE)

• Benefits of PSE
  – If a bus voltage phasor or a line current phasor is not measured, it can be calculated from other phasor measurements (virtual PMU data)
  – Dynamic state estimation and model validation
    • calculate the internal states of synchronous machines
    • Generator model validation and identification

• PSE approaches
  – Linear state estimator – least-squares fit with no iterations
    • Three-phase – Jones and Thorp (Jones, MS thesis 2011)
  – PSE with phase angle bias correction – RPI, iterative LS fit to estimate angle bias, current scaling, and transformer taps
Phase Angle Bias – Equations

Bus 3 is a redundant bus

PMU A

PMU B

$\tilde{V}_1 \quad \tilde{I}_1 \quad \tilde{V}_3 \quad \tilde{I}_2 \quad \tilde{V}_2$

PMU A at Bus 1

Voltage Angle

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

Current Angles

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

Same angle bias variable $\phi_A$ for all PMU channels

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

PMU B at Bus 2

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

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

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

PMU Node  ---  PMU Current  △ Estimated Node

Voltage

Angle

Current

Angles
Current Scaling Factors – Equations

PMU A at Bus 1

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

PMU B at Bus 2

\[
I_{23} - I_{23}^{\text{meas}} = e_{I_{23}} \\
\vdots \\
(1 + c_{2k})I_{2k} - I_{2k}^{\text{meas}} = e_{I_{2k}}
\]

Independent estimates of \( \tilde{V}_3 \) should agree.

From: Luigi Vanfretti (KTH), Scott Ghiocel (Mitsubishi)
RT-PSE

• NSF project to implement a real time phasor-only state estimator with Grid Protection Alliance (GPA) for New York and New England 765/345/230 kV system: from Western NY (Niagara Falls) to Eastern Maine
  • Connect NY and NE as a single SE – possible as NY/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%
  • It will be implemented as an action adaptor on the GPA’s OpenPDC for real-time operation.
RT-PSE Service Concept

From: Russell Robertson (GPA)
PSE Results from Linking 2 Control Areas

• Two control areas
  – Area 1 has 21 PMUs (on 345 and 230 kV buses) and Area 2 has 35 PMUs (345 kV buses)
  – There is a tie-line between these two areas with PMU voltage measurements on both buses and a PMU current measurement, allowing the two control areas form one observable island (unless the line is out).
  – The flow on a second tie-line (no PMU measurements) can be calculated from the PSE solution

• Angle Bias Calculation
  – Area 1: phase $a$ as positive sequence reference; Area 2: phase $b$ as positive sequence reference; the PSE successfully found the 120 degree phase shift, as part of the angle bias calculation
  – After the 120 degree phase shift is accounted for, the angle bias is, in general, small (less than 1 degree).
PSE Results from Linking 2 Control Areas

• Using total vector error (TVE) to evaluate PMU data accuracy
  – Assume PSE solution is accurate
  – Current scaling important

\[ TVE(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{X_r(n)^2 + X_i(n)^2}} \]

• Under ambient conditions
  • With angle bias correction: Raw voltage measurement average TVE was 0.35% of PSE
  • Without angle bias correction: Raw voltage measurement average TVE was 1.5%

Figure E1. The 1% TVE criterion shown on the end of a phasor
PSE Results from Linking 2 Control Areas

• Total number of PMU voltages
  – 56 voltage measurements directly from PMUs
  – 70 virtual PMU voltage measurements
  – Total of 126 buses observable

• Applications of real and virtual PMU measurements
  – Virtual PMU voltage and current measurements from generators: importance of accurate PMU measurements – the angle across a line connected to a generator is less than 0.1 degree
  – Virtual PMU voltage and current measurements from wind turbine-generators – study of reactive power control performance, and if wind data is available, for also studying active power control
  – Interface flow between the two areas during major disturbances
  – STATCOM PMU voltage and current output – study of voltage regulation effect

From: Emily Fernandes (VELCO), Dan Isle & De Tran (NYISO), Frankie Zhang & Dave Bertagnolli (ISO-NE), George Stefopoulos & Bruce Fardanesh (NYPA), ...
STATCOM Dynamics Calculation

- STATCOM voltage regulation

\[
\frac{K}{T \cdot s + 1}
\]

- STATCOM VI plot (using PSE calculated data), with droop line superimposed \((1/K)\)
- In dynamic response, the PMU data would not follow strictly the droop line – allowing the identification of the time \(T\)
STATCOM Parameter Identification Results

- Measured vs dynamic simulation using identified $K$ and $T$

From: Wei Li (KTH)
Conclusions

• Need systematic framework and tools to manage “big data” in power systems and to ensure high data quality

• Biggest barrier in using PMU data is data quality – and the biggest data quality issue is lack of data form some PMUs over extended periods of time. (We can handle occasional data loss due to communication network congestion.)

• High data quality allows applications to be deployed with confidence

• Also need diversified synchronized time-tagged data, like generator rotor angles and speeds, such that more advanced applications can be implemented
References