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Analysis of Large Amount of PMU Data and Voltage Stability Analysis of Wind Farms using PMU Data

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Topics

- NSF/DOE CURENT ERC
- “Big data” analysis for PMU data
- Voltage stability analysis of for median-voltage transmission systems with wind farms
CURENT – NSF/DOE ERC

• Center for Ultra-Wide Area Resilient Electric Energy Transmission Networks

• One of only two ERCs funded jointly by NSF and DOE. Core budget: ~$4M/year for 5+5 years but highly leveraged to be able to fully support programs.

• CURENT is the only ERC devoted to wide area controls and one of only two in power systems.

• Partnership across four universities in the US and three international partner schools. Many opportunities for collaboration.

• Presently CURENT has close to 20 industry members.

• Center began August 15, 2011
CURENT Leadership

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CURENT Engineering Research Center

• Program elements include:
  • Outreach (K-12 education) – summer camps
  • Research experience for undergraduates
  • Entrepreneurship training
  • Industry program
  • Systems engineering approach
  • International collaboration
Why CURENT?

• Energy sustainability is one of the most fundamental societal challenges.

• Changing and uncertain generation mix; reliance on fossil fuels creates significant environmental and national security issues.

• Solutions are being pursued which focus mostly on source and load.
  ➢ Renewable energy sources, mainly wind and solar
  ➢ Electric vehicles and energy storage
  ➢ Energy efficient lighting, appliances, and buildings

These solutions require a fundamentally new approach to electric power delivery
US Wind and Solar Resources

Best wind and solar sources are far from load centers.

Transmission networks must play a central role in integration.

CURENT Vision

- A nation-wide transmission grid that is fully monitored and dynamically controlled for high efficiency, high reliability, low cost, better accommodation of renewable sources, full utilization of storage, and responsive load.

- A new generation of electric power and energy systems engineering leaders with a global perspective coming from diverse backgrounds.
PMU Locations in North America

Installations:
- 1100+ PMUs
- 150+ data concentrators (PDCs)

New challenges:
- Data quality
- Networking
- Control room integration
- Wide-area monitoring & control

Source: NASPI, October 2013
What is CURENT?

Wide Area Control of Power Grid

Measurement & Monitoring

Communication

Actuation
**Major Research Questions**

**Future Power System Control Architecture**

- Information flow and system monitoring
  - PMU data, smart meter data, ...: *Big data*?
  - How do we make get the most information out of the data?
- Control architecture
  - Ultra-wide-area control with communication systems
  - Integration of renewable resources (near 100% renewables?)
- Control equipment economics and optimization

➤ Design needs to be a series of trade-offs between communication needs, device sophistication, resiliency, speed of response, economic performance and device reliability vs. system reliability.
Big Data in Power Systems

- PMU data is considered to be a source of Big Data in power systems
  - 30/50/60 points per second, 24/7/365: GB/TB per day
  - Control regions such as New York and New England, will have about 40 PMUs each, with 6-12 data channels per PMU – averaging one PMU per 1,000 MW of generation

- PMU data is envisioned to provide the following capabilities:
  - Disturbance triggering
  - Disturbance location and recognition (what kind of disturbance, e.g., loss of generation, loss of line)
  - Assessing the severity of the disturbance and its impact on the power system
  - Avoiding cascading failure in interconnected power systems
  - What kind of Big Data tools can be used? Is there a Big Data Toolbox somewhere?
Space-Time View of PMU Data

![Diagram showing space-time view of PMU data with PMU channels, space, time, and data blocks labeled with symbols for missing, bad, and cyber attack data points.](image-url)
PMU Data Housekeeping Chores

• Fill in missing data
• Correct bad data
• Detect cyber attacks – beyond the routine black-hole and gray-hole attacks
• Check on system oscillations
• Alarm on disturbances
• Figure out what kind of disturbances – either from operator log or use disturbance characterization
• Figure out if there are any correlations between the disturbances and the possibility of cascading blackouts

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

- From a 2003 article with Alex Bykhovsky (ISO-NE) using PMU data from Northfield Mountain

- Frequency at Northfield for loss of NE HVDC 1 pole
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 particular bus, it is possible to estimate roughly what the PMU values at the nearby buses are.

Fig. 7. Current magnitudes of PMU data (9 current phasors out of 37 phasors)

Fig. 3. Original frequency profile
Low-Rank Power System Data Matrix

- Joint work with Prof. Meng Wang 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 of 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: keep only significant singular values and vectors
  - Missing PMU data recovery – matrix completion using convex programming
  - Detection of PMU data substitution – sum of a low-rank matrix and a sparse matrix, using convex programming decomposition algorithm
  - Disturbance and bad data detection – when second and third singular values become large
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

- Original
- One SV
- Two SVs
- RMS error
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)
Missing Data Example

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

- 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.
Data Substitution Attacks

Diagram:

- Bus 1
- Z_{13}
- Bus 2
- Z_{23}
- Bus 3
Data Substitution Attacks

- Measurements: the phasors $V_1, V_2, I_{12}, I_{23}$. Estimate the phasor $V_3$. 
Data Substitution Attacks

- Measurements: the phasors $V_1$, $V_2$, $I_{12}$, $I_{23}$. Estimate the phasor $V_3$.
- Redundancy in measurements can be used to detect bad data.

$$V_3 = V_1 - I_{13}Z_{13} = V_2 - I_{23}Z_{23}$$
Data Substitution Attacks

- Measurements: the phasors $V_1, V_2, I_{12}, I_{23}$. Estimate the phasor $V_3$.
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- Cyber data attack: manipulate the phasors $I_{12}$ and $I_{23}$ simultaneously.
Data Substitution Attacks

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- Redundancy in measurements can be used to detect bad data.
- Cyber data attack: manipulate the phasors $I_{12}$ and $I_{23}$ simultaneously.
- Can result in significant error in the phasor $V_3$, yet cannot be detected by state estimation.
Cyber Data Attacks

• Worst-case interacting bad data (Liu, Ning, & Reiter 2011)
• An intruder with the system topology information (not necessarily, Kim, Tong, & Thomas 2013) simultaneously manipulate multiple measurements so that these attacks cannot be detected by any bad data detector.
• Cyber data attacks can potentially lead to significant errors to the outcome of state estimation.
• Existing approaches
  ◆ Usually protect key PMUs to avoid these attacks (Kosut, Jia, Thomas, & Tong 2010, Kim & Poor 2011, Bobba et al. 2010, Dán & Sandberg 2010)
  ◆ Sedghi & Jonckheere 2013: Detection of cyber data attacks in SCADA system. Assume the measurements at different time instants are i.i.d. distributed.
Attack model

• At each instant, the intruder injects errors to the estimation of system states by manipulating multiple measurements.
• Voltage and current phasor measurements can be represented by linear functions of state variables.
• The additive errors to phasor measurements are consistent with each other and cannot be detected by bad data detectors.
• The intruder can only attack a small number of PMUs continuously.
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Assumptions

\[ M = \bar{L} + \bar{C}W^T + N \]

- \( \bar{L} \): low-rank. From correlations in measurements.
- \( \bar{C} \): column sparse. The intruder has limited access to the system
- \( N \): \( \|N\|_F \leq \varepsilon \)

Given \( M \) and \( W \), how could we identify \( \bar{L} \) and \( \bar{C} \)?
Connection to Related Work

• Xu, Caramanis, & Sanghavi 2012: Decomposition of a low-rank matrix and a column-sparse matrix.

• Our methods and proofs are built upon those in Xu, Caramanis, & Sanghavi 2012, with extension to general cases.
Connection to Related Work

- Mardani, Mateos & Giannakis 13: Decomposition of a low-rank matrix plus a compressed sparse matrix. Internet traffic anomaly detection.

- Our focus: column-sparse matrices, $W$ is arbitrary.
Our Approach

- Find \((L^*, C^*)\), the optimum solution to the following optimization problem

\[
\min_{L \in \mathbb{C}^{t \times p}, C \in \mathbb{C}^{t \times n}} \|L\|_* + \lambda \|C\|_{1,2} \quad \text{s.t.} \quad \|L + CW^T - M\|_F \leq \varepsilon \quad (1)
\]

- \(\|L\|_*\): sum of singular values of \(L\)
- \(\|C\|_{1,2}\): sum of column norms of \(C\)
- Compute the SVD of \(L^* = U^*\Sigma^*V^*\dagger\)
- Find column support of \(D^* = C^*W^T\), denoted by \(J^*\)
- Return \(L^*, U^*,\) and \(J^*\)
- (1) is convex and can be solved efficiently.
Theoretical Guarantee

Theorem (Noiseless measurements, $n = 0$)
With a properly chosen $\lambda$, the solution returned by our method
1. identifies the PMU channels under attack.
2. identifies the measurements that are not attacked.
3. recovers the correct subspace spanned by actual phasors.

Theorem (Noisy measurements, $n \neq 0$)
With a properly chosen $\lambda$, the solution returned by our method is sufficiently close (with distance depending on the noise level) to a solution that meets 1-3.
Numerical Results

- Simulate the case that the intruder alters the PMU channels that measure the phasors $I_{12}, I_{52}, I_{13},$ and $I_{43}$.
- The voltage phasor estimates of Buses 2 and 3 are corrupted.

Actual values and corrupted values

Column norms of the recovered error matrix
Disturbance Detection using PMU Data and Singular Value Analysis

• Organize PMU data into different regions, like Central New York, West NY, North NY, etc.

• Analyze voltage magnitude or frequency channels from PMUs in a region with Singular Value Decomposition (SVD)

• Steady state: relationships between measurements at different PMUs remain the same → one large singular value, and the rest are very small singular values

• During a disturbance, the relationships between different PMUs will start to differ → 2nd and 3rd largest singular values will increase

• Disturbance location: region with the largest 2nd largest singular value

• Analysis and plots by Josh Klimaszewski and Tony Jiang
Disturbance 2 (Voltage Magnitudes)

Window Size (3.33 seconds/100 samples)
Step Size (1.66 seconds/50 samples)

2^{nd} largest SV
Disturbance 2 (Voltage Magnitudes)

Window Size (3.33 seconds/100 samples)
Step Size (1.66 seconds/50 samples)

Window Size (.67 seconds/20 samples)
Step Size (.67 seconds/20 samples)
Next Steps

• Leverage the low-dimensional structures in high-dimensional data to address the challenges in data acquisition, storage, and information extraction.

• Use block data matrices for disturbance location and identification

• Link disturbance analysis to power system states
Voltage Stability Analysis Topics

- **AQ-bus Voltage Stability Analysis Method**
  - For quasi-steady state voltage stability analysis
  - An alternative to the Continuation Power Flow Method

- Analyzing voltage stability margin related to wind farm operations in median voltage transmission systems
Voltage Stability Analysis: AQ-Bus Method

- A difficulty with power flow based voltage stability analysis is that the Jacobian matrix (in Newton-Raphson formulation) is singular at the voltage collapse point.
- Continuation Power Flow Method has two steps: (1) project the starting point for a new solution with higher power transfer, and (2) iterate till convergence.
- The AQ-bus method extends the angle of the voltage collapse bus. In doing so, reduce the size of the Jacobian matrix by 1, and eliminate the singularity at the voltage collapse point.
- The single-load stiff-source example in the following slides illustrate this concept.
Treating the load bus as a PQ bus, the Jacobian is

\[ J = -\frac{1}{X} \begin{bmatrix} V_L E \cos \theta_s & E \sin \theta_s \\ V_L E \sin \theta_s & 2V_L - E \cos \theta_s \end{bmatrix} \]

The Jacobian is singular when

\[ \det J = V_L E \left( 2V_L \cos \theta_s - E \right) / X = 0 \]
PV Curves and Angle Separation

- Single-load VSA with constant power factor
- Load bus angle (angle separation) is seldom analyzed in VSA
New Idea: Specify the Angle for VSA

- Specify load bus angle, so the number of unknowns is reduced by 1
- Remove load $P$ equation (load power not enforced):

\[ J = -\frac{1}{X} \begin{bmatrix} V_L E \cos \theta_S & E \sin \theta_S \\ V_L E \sin \theta_S & 2V_L - E \cos \theta_S \end{bmatrix} \]

- New matrix is nonsingular at the maximum loading point
Advantages of AQ-Bus Method

- Calculate VS margins by increasing AQ-bus angle
- Accommodates multiple loads and generators
- Allows for various load types, such as constant power factor loads
- Includes all features of conventional power flow: tap changers, generator reactive power limits, sparse matrices, decoupled power flow, etc.
- Readily generalized to large power systems

<table>
<thead>
<tr>
<th>Bus types</th>
<th>Bus representation</th>
<th>Fixed values</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>Generator buses</td>
<td>Fixed active power generation and bus voltage</td>
</tr>
<tr>
<td>PQ</td>
<td>Load buses</td>
<td>Fixed active and reactive power consumption</td>
</tr>
<tr>
<td>AV</td>
<td>Swing bus (generator)</td>
<td>Fixed angle (A) and voltage magnitude</td>
</tr>
<tr>
<td>AQ</td>
<td>Load bus</td>
<td>Fixed voltage angle and reactive power consumption</td>
</tr>
</tbody>
</table>
Example: NPCC 48-Machine System
NPCC System: Contingency Analysis

Generator schedule for 48-machine system

<table>
<thead>
<tr>
<th>Generator Bus #</th>
<th>Bus Type</th>
<th>$\beta_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>AV (swing)</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>PV</td>
<td>0.10</td>
</tr>
<tr>
<td>36</td>
<td>PV</td>
<td>0.80</td>
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Load schedule for 48-machine system

<table>
<thead>
<tr>
<th>Load Bus #</th>
<th>Bus Type</th>
<th>$\alpha_\ell$</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>$AQ$</td>
<td>-</td>
<td>0.95 lag</td>
</tr>
<tr>
<td>4</td>
<td>$PQ$</td>
<td>0.50</td>
<td>0.95 lag</td>
</tr>
<tr>
<td>15</td>
<td>$PQ$</td>
<td>0.25</td>
<td>0.95 lag</td>
</tr>
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Contingency list for 48-machine system

<table>
<thead>
<tr>
<th>#</th>
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<th>Power Flow</th>
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<tbody>
<tr>
<td>A</td>
<td>73–74</td>
<td>72 MW</td>
</tr>
<tr>
<td>B</td>
<td>8–73</td>
<td>97 MW</td>
</tr>
<tr>
<td>C</td>
<td>2–37</td>
<td>53 MW</td>
</tr>
<tr>
<td>D</td>
<td>3–2</td>
<td>295 MW</td>
</tr>
<tr>
<td>E</td>
<td>3–18</td>
<td>50 MW</td>
</tr>
</tbody>
</table>
PV Curves & Contingency Analysis

Active power loading margin at AQ-bus (Bus 16) (pu)

AQ-bus (Bus 16) voltage magnitude (pu)

Line Trip Contingency Analysis based on PV Curves

Base case

Contingency list for 48-machine system

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Active power margin (ΔP) at AQ Bus (pu)
Figure 1. Wind Hub Ring Bus and Wind Plant Equivalent Models

Voltage Variations with Outage of Strong Link

- SCADA data showing voltage response on Buses 21, 22, and 25, with Line 22-25 out of service. The voltage jumps are WTG trips.
- The project is to determine wind turbine reactive power control models and voltage stability limit.
- The wind farms cannot produce full output in this scenario.

~ 3 hours Capacitor switchings

Time (sec)
Hybrid Voltage Stability Analysis using PMU Data

• Measurement-based approach
  - Identify a region with voltage stability issues
  - Use measurement data to obtain Thevenin equivalent for the sources or inflows into the region: Vanfretti least-squares method
  - Use AQ-bus method to compute the voltage stability margin based on the Thevenin equivalents, the line parameters, and the wind farm operation (voltage control, constant power factor, etc.)
BPA JC VS Analysis Update

• 24-hour data at 2-second interval provided by Tony Faris on June 2, 2014 during BPA visit
• SCADA data at JC: $V, P, Q$, and also $V$ at East and West Buses
• No shunt capacitor information at the wind farms
• Intent is to perform offline computation on a daily basis to verify the reliability and usefulness of the computation algorithm before considering the tool for real-time information support
BPA JC 24-hr VS Analysis Process

- Performs a new VS margin calculation every 5 minutes (note: sliding window also possible)
- Complex code to figure out the shunt compensation in the wind farms
- The \( AQ \)-technique works well, readily going beyond the voltage collapse point
- Thevenin equivalent estimation \( (E_{TH} \text{ and } X_{TH}) \) is difficult during periods when the voltages and flows are stationary or vary widely. Problem may be solved with longer windows
- 24-hour data requires about 15 minutes to compute
DEMO
BPA JC 24-hr VS Analysis

Welcome to our GUI. In this GUI you are able to input an Excel data file to calculate multiple outcomes. To run the program, press Start and select your Excel file. For the figures along the top row and the right side the color green corresponds to the San Juan bus and purple corresponds to the Moony bus. Blue is the Wind hub.

- Power Jones Canyon to San Juan (p.u.)
- Wind Hub Power (p.u.)
- Wind Hub Power at Wind Power Transfer (p.u.)
- Voltage Stability Margin (p.u.)
- Thevenin E (p.u.)
- Voltage Magnitude at West Substation (p.u.)
- Voltage Magnitude at East Substation (p.u.)
- Thevenin X (p.u.)
Next Steps

• Improved Thevenin equivalent estimation
  • Corsi-Taranto method
• Use of PMU data, not just SCADA data
• Other potential study areas with wind power coming into median voltage transmission systems
References


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Phasor Measurement Equipment

GPS time-tagged measurement of 3-phase voltages and currents, at 30 or 60 samples per second
FNET Visualization

FDR recordings in Eastern Interconnection – Feb 2, 2008: plot of frequencies at various locations

Prof. Yilu Liu, University of Tennessee, Knoxville
PMU Data Single-Channel Analysis

- Decision tree to classify disturbances
Disturbance 1 (Voltage Magnitudes)

Window Size (3.33 seconds/100 samples)
Step Size (1.66 seconds/50 samples)
Disturbance 2 (Frequencies)

Window Size (3.33 seconds/100 samples)
Step Size (1.66 seconds/50 samples)