Predictive Wide-Area Modeling of Large Power System Networks Using Synchronized Phasor Measurements

Aranya Chakrabortty
North Carolina State University, Raleigh, NC
ISGT 2014, Washington DC
Main trigger: 2003 Northeast Blackout

2 Main Lessons Learnt from the 2003 Blackout:

1. Need significantly higher resolution measurements
   ➞ From traditional SCADA (System Control and Data Acquisition) to PMUs (Phasor Measurement Units)

2. Local monitoring & control can lead to disastrous results
   ➞ Coordinated control instead of selfish control
Applications so far

1. Oscillation Monitoring Algorithms
   1.1 Mode meter – PNNL
   1.2 Real-time monitor – WSU, BPA
   1.3 Ringdown & ambient – UW, MTU
   1.4 Predictive models – RPI, NCSU, Imperial
   1.5 Mode shapes – WSU, KTH, SCE
   1.6 Voltage stability – ABB, SCE, Quanta

2. Phasor State Estimator
   2.1 Three-phase PSE – VA Tech, Dominion
   2.2 PMU placement algorithms – NEU, RPI
   2.3 Bad data detectors – NEU, RPI, ISO-NE
   2.4 Dynamic PSE – VA Tech, PNNL
   2.5 PSE installations - CURENT
Wide-Area Modeling

- Periodic updates of the grid models is **imperative** for reliable monitoring & control

Massive volumes of PMU data from various locations

Dynamic models of the grid at various resolutions

\[
\dot{x} = f(x, y, \theta)
\]

\[
0 = g(x, y, \theta)
\]
Grid Dynamic Models

• Synchronous Generator Models

\[
\delta_i = \omega_i - \omega_s \\
M_i \ddot{\omega}_i = P_{mi} - D_i (\omega_i - \omega_s) - P_i^G
\]

\[
\tau_i \dot{E}_i = -\frac{x_{di}}{x_{di}'} E_i + \frac{x_{di} - x_{di}'}{x_{di}'} V_i \cos(\delta_i - \theta_i) + E_{Fi} \quad \Rightarrow \quad E_{Fi} = \bar{E}_{Fi} + E_i
\]

Control input
Excitation voltage

• Power Flow Equations

\[
E_i \angle \delta_i \\
V_i \angle \theta_i \\
r_{ik} + jx_{ik} \quad V_k \angle \theta_k
\]

\[
P_{ik}^L \quad \Rightarrow \quad P_{ik}^L + jQ_{ik}^L
\]

Bus voltage and phase angle
Algebraic variables
Measured by PMU

\[
P_i^G = \frac{E_i V_i}{x_{di}'} \sin(\delta_i - \theta_i) + \left( \frac{x_{di} - x_{qi}}{2x_{qi} x_{di}'} \right) V_i^2 \sin(2(\delta_i - \theta_i))
\]

\[
Q_i^G = \frac{E_i V_i}{x_{di}'} \cos(\delta_i - \theta_i) - \left( \frac{x_{di} - x_{qi}}{2x_{qi} x_{di}'} - \frac{x_{di} - x_{qi}}{2x_{qi} x_{di}'} \cos(2(\delta_i - \theta_i)) \right) V_i^2
\]
Grid Dynamic Models

**Load Models**

\[
P^L_j = a_j V_j^2 + b_j V_j + c_j \]
\[
Q^L_j = e_j V_j^2 + f_j V_j + g_j \]

\[\begin{align*}
a_j, e_j &= \text{constant impedance} \\
b_j, f_j &= \text{constant current} \\
c_j, g_j &= \text{constant power}
\end{align*}\]

**Transmission Line Model**

\[
P_{ij} = G_{ij} V_i^2 + B_{ij} V_i V_j \sin(\theta_i - \theta_j) - G_{ij} V_i V_j \cos(\theta_i - \theta_j) \]
\[
Q_{ij} = (B_{ij} - B_{ij}^c) V_i^2 - B_{ij} V_i V_j \cos(\theta_i - \theta_j) - G_{ij} V_i V_j \sin(\theta_i - \theta_j). \]

\[\text{Pi-model}\]
• Total Network Model

\[
\begin{bmatrix}
\Delta \dot{\delta} \\
M \Delta \dot{\omega} \\
\Delta \dot{E}
\end{bmatrix} =
\begin{bmatrix}
0 & I & 0 \\
-L(G) & -D & -P \\
K & 0 & J
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E
\end{bmatrix} +
\begin{bmatrix}
0 \\
\text{col}_{i=1}^{1}(1_n(\gamma_i)) \\
\text{col}_{i=1}^{1}(1_n(\rho_i))
\end{bmatrix}
due to load
+ \begin{bmatrix}
0 & 0 \\
0 & I \\
I & 0
\end{bmatrix}
\begin{bmatrix}
\Delta P_m \\
\Delta E_F
\end{bmatrix} \quad …(1)
\]

\[L(G) = \text{fully connected network graph}\]

Controllable inputs

\[\Delta P_m\]

• low bandwidth
• used mostly for AGC
• mechanical system wear and tear

\[\Delta E_F\]

• much higher bandwidth
• used for oscillation damping
• electrical input

Output Equation

\[y = \text{col}_{i \in S}(\Delta V_i, \Delta \theta_i). \quad …(2)\]
Use PMU data to Construct Inter-area Clustered Models

**WECC (500 KV)**

1. **Western cluster** – Mitchel River, Antioch, Marshall, Pisgah, Tucksagee, Shiloh, North Greenville
2. **Eastern cluster** – Harrisburg, Peacock, Allen, Lincoln, Oakboro
3. **Northern cluster** – Ernst, Sadler, Rural Hall, North Greensboro
4. **North-eastern cluster** – Pleasant Garden, East Durham,
5. **Southern cluster** – Shady Grove, Anderson, Hodges, Bush River

**Duke Energy (500 & 235 KV)**

- **S Cluster**: Bush River, Anderson, Pisgah
- **W Cluster**: Antioch, Rural Hall
- **N Cluster**: Ernst, Oakboro
- **E Cluster**: Pleasant Garden
- **NE Cluster**: PMU Locations

**PMU Locations**
- Pleasant Garden
- Antioch
- Bush River
- Lugo
- Malin
- Pacific AC Intertie
- Pacific HVDC Intertie
- Table Mountain
- Vincent
- Lugo
- Oregon
- Washington
- Canada
- Utah
- Wyoming
- Montana
- New Mexico
- Arizona
- Baja CA (Mexico)
- Mexico
- Los Angeles
- Nebraska Cluster
- N Cluster
- W Cluster
- S Cluster
- E Cluster
- NE Cluster
- PMU

[Diagram of electrical grid connections and PMU locations]
Wide-Area Model Reduction

6-machine, 19-bus, 3-area power system
Wide-Area Model Reduction

6-machine, 19-bus, 3-area power system

PMU measurements

Area 1

- How to approach this model-reduction problem solely using PMU measurements now?
- Operators may be more interested in this model to study inter-area oscillations
After Kron Reduction Full-order System Looks Like:

\[
\begin{bmatrix}
\Delta \omega_1^1 \\
\vdots \\
\Delta \omega_{m_1}^1 \\
\Delta \omega_1^2 \\
\vdots \\
\Delta \omega_{m_2}^2 \\
\vdots \\
\Delta \omega_1^r \\
\vdots \\
\Delta \omega_{m_r}^r
\end{bmatrix}
\begin{bmatrix}
\mathcal{M}_1^{-1} \mathcal{L}_1 + \mathcal{K}_1 \\
\vdots \\
\mathcal{M}_2^{-1} \mathcal{L}_2 + \mathcal{K}_2 \\
\vdots \\
\mathcal{M}_r^{-1} \mathcal{L}_r + \mathcal{K}_r
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_1^1 \\
\vdots \\
\Delta \delta_{m_1}^1 \\
\Delta \delta_1^2 \\
\vdots \\
\Delta \delta_{m_2}^2 \\
\vdots \\
\Delta \delta_1^r \\
\vdots \\
\Delta \delta_{m_r}^r
\end{bmatrix}
\]

Cast it as a Nonlinear Least Squares parameter estimation problem.
Pre-Filtering of PMU data – Examples from WECC disturbances

Oscillations

Bus Voltage (pu)

0 50 100 150 200 250 300

Time (sec)

Band-pass Filter

Choose pass-band covering typical swing mode range

Quasi-steady State

Slow Voltage (pu)

0 50 100 150 200 250 300

Time (sec)
Pre-Filtering + Mode Separation in PMU data

Oscillations

Interarea Oscillations

- Can use modal identification methods such as: ERA, Prony, Steiglitz-McBride

\[ y(t) = \alpha_0 + \alpha_1 e^{-d_1 \pm j\Omega_1 t} + \cdots + \alpha_{r-1} e^{-d_{r-1} \pm j\Omega_{r-1} t} + \alpha_r e^{-d_r \pm j\Omega_r t} + \cdots + \alpha_{n-1} e^{-d_{n-1} \pm j\Omega_{n-1} t}, \]

\[ y^E(t), \text{ inter-area modes} \quad + \quad y^I(t), \text{ intra-area modes} \]
Model Identification via $L_1$-$L_2$ minimization

Extract slow oscillatory components of PMU data $y(t)$ using modal decomposition methods, then cast as a sparse optimization problem:

$$\min_{A_d,B_d} \frac{1}{2} \left\| X_i^{m+1} - A_{d_i} X^m - B_{d_i} u^m \right\|_2^2 + \lambda \sum_i |L^E_{ij}|$$

Convexify the problem as $L_2$-$L_1$ opt.

IEEE 39-Bus System

Decentralized Topology ID by each RTO

Area 1  Area 2  Area 3  Area 4
Structured Model Identification from PMU data

Joint work with
Southern California Edison

A_i : i^{th} area
P_i : Pilot bus for the i^{th} area
ASG_i : Aggregated Synchronous Generator representing area A_i
E_i \angle \delta_i : Voltage Phasor of the internal EMF of ASG_i
V_i \angle \theta_i : Voltage Phasor at pilot bus P_i
jx_i : Internal Thevenin reactance of ASG_i
r_{ij} : Resistance of transmission line between P_i and P_j
x_{ij} : Reactance of transmission line between P_i and P_j
p_{ij} : Active power flow between buses P_i and P_j
\hat{I}_i : Current Phasor injected at P_i^{th} bus by ASG_i
Intra-tie Impedance: June 18 Line Trip Event
Intra-tie Impedance Estimation from PMU data

- It was observed that each area has a different pre- and post-fault reactance value. Values for June 18th 2010 and Jun 23rd 2010 events are listed:

<table>
<thead>
<tr>
<th>Area</th>
<th>Pre-fault Impedance ohms</th>
<th>Post-fault Impedance ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colstrip</td>
<td>24.8888</td>
<td>30.0108</td>
</tr>
<tr>
<td>Grand Coulee</td>
<td>9.3117</td>
<td>6.6197</td>
</tr>
<tr>
<td>Malin</td>
<td>-3.2501</td>
<td>5.8459</td>
</tr>
<tr>
<td>Vincent</td>
<td>19.8367</td>
<td>21.8125</td>
</tr>
<tr>
<td>Palo Verde</td>
<td>34.4677</td>
<td>32.7578</td>
</tr>
</tbody>
</table>

SVC at Malin

<table>
<thead>
<tr>
<th>Area</th>
<th>Pre-fault Impedance ohms</th>
<th>Post-fault Impedance ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colstrip</td>
<td>26.5861</td>
<td>27.5240</td>
</tr>
<tr>
<td>Grand Coulee</td>
<td>4.1314</td>
<td>3.1600</td>
</tr>
<tr>
<td>Malin</td>
<td>0.9872</td>
<td>-1.7481</td>
</tr>
<tr>
<td>Vincent</td>
<td>17.0301</td>
<td>17.4487</td>
</tr>
</tbody>
</table>
Inertia & Damping Estimation

Recall Swing Equations:

\[
\begin{bmatrix}
M_1 & 0 & 0 & 0 \\
0 & M_2 & 0 & 0 \\
0 & 0 & M_3 & 0 \\
0 & 0 & 0 & M_4 \\
\end{bmatrix}
\begin{bmatrix}
\ddot{\delta}_1 \\
\ddot{\delta}_2 \\
\ddot{\delta}_3 \\
\ddot{\delta}_4 \\
\end{bmatrix}
= \begin{bmatrix}
\Delta_1 & E_1E_2Y_{12} & E_1E_3Y_{13} & E_1E_4Y_{14} \\
E_1E_2Y_{12} & \Delta_2 & E_3E_2Y_{32} & E_4E_2Y_{42} \\
E_1E_3Y_{13} & E_3E_2Y_{32} & \Delta_3 & E_3E_4Y_{34} \\
E_1E_4Y_{14} & E_4E_2Y_{42} & E_4E_3Y_{34} & \Delta_4 \\
\end{bmatrix}
\begin{bmatrix}
\dot{\delta}_1 \\
\dot{\delta}_2 \\
\dot{\delta}_3 \\
\dot{\delta}_4 \\
\end{bmatrix}
- \begin{bmatrix}
D_1 & 0 & 0 & 0 \\
0 & D_2 & 0 & 0 \\
0 & 0 & D_3 & 0 \\
0 & 0 & 0 & D_4 \\
\end{bmatrix}
\begin{bmatrix}
\dot{\delta}_1 \\
\dot{\delta}_2 \\
\dot{\delta}_3 \\
\dot{\delta}_4 \\
\end{bmatrix} + P_m
\]

- Parameters appear in nonlinear form
- The input is not known (modeled as impulse for convenience)

Known from previous steps of estimation
Wide-Area Models are Essential for Wide-Area Monitoring

- There are commonly used metrics that operators like to keep an eye on
- Use wide-area models + PMU data to assess transient stability margins – Energy functions/Lyapunov functions

\[ S = S_1 + S_2 = \sum_{j=1}^{n(n-1)/2} \int_{\delta_{ij}}^{\pi} \psi_j(k) \, dk + \sum_{j=1}^{n} \frac{M_j}{2} \xi_j^2 \]

\[ = \frac{E_1 E_2}{X_e} \left[ \cos(\delta_{op}) - \cos(\delta) + \sin(\delta_{op})(\delta_{op} - \delta) \right] + H\omega^2 \]

Recall storage functions for passive systems.
Total Energy = Kinetic Energy + Potential Energy

August 4, 2000 event in WECC

- Total energy decays exponentially – *damping stability*
- Total energy *does not* oscillate – *Out - of - phase osc.*
Wide-Area Models are Useful for Wide-Area Control

2 critical problems

- **Inter-area oscillation damping** – output-feedback based MIMO control design for the full-order power system to shape the closed-loop phase angle responses of the reduced-order model

- **System-wide voltage control** – PMU-measurement based MIMO control design for coordinated setpoint control of voltages across large inter-ties
  - FACTS controllers (SVC, CSC, STATCOM)

Smart Islanding – max flow min-cut
Wide-Area Power Flow Control using PMUs and FACTS

Semi-Supervisory Power Flow Dispatch Control

- From Power Flow Controllers in each area
- To control center dispatch decisioning
- To damping actuators in Area 1

Adaptation Loop
Wide-Area UPFC/CSC
Damping Controller
Time-varying Models
Kalman Filtering & Phasor State Estimator
Reconfiguring Boundary Control
PDC for Area 1

Local Control System for Area 1

Communication links

IEEE 118-bus power system

Area 1
Area 2
Area 3
Area 4
Area 5
We have just completed setting up an intra-campus local PMU communication network with UNC Chapel Hill and Duke University.
Conclusions

1. WAMS is a tremendously promising technology for control + signal processing researchers

2. Control + Communications + Computing must merge

3. Plenty of new research problems – EE, Applied Math, Computer Science

4. Plenty of new system identification + big data analytics problems

5. Right time to think mathematically – Network theory is imperative

6. Right time to pay attention to the bigger picture of the electric grid

7. Needs participation of young researchers!

8. Promises to create jobs and provide impetus to power engineering
Thank You

Email: achakra2@ncsu.edu

Webpage: http://people.engr.ncsu.edu/achakra2