Topic 6: Wide Area Measurements

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Wide-Area Measurement

• We would like to deploy several sensors across the grid:
  • To monitor the operation of the grid (almost) in real-time.

• Applications:
  • Angle and frequency monitoring
  • Post-mortem analysis (disturbances and system failures)
  • Voltage and voltage stability monitoring
  • Improved state estimation
  • Steady-state benchmarking
Wide-Area Measurement for Situational Awareness

• WAM can help us achieve Wide-area Situational Awareness:

• Situational Awareness:

Understanding the current environment and being able to accurately anticipate future problems to enable effective actions.

• To be able to optimally and yet robustly operate the grid.

• Key Sensor: Phasor Measurement Unit (PMU)
Synchronized Measurements

• A PMU at a substation measures voltage and current phasors:
  • Very precise synchronization with μs accuracy.
  • Compute MW/MVAR and frequency.

• Measurements are reported at a rate of 20-60 times a second.
  • Can track grid dynamics in real time
  • Traditional SCADA refresh rate is seconds to minutes
Synchronized Measurements

• Each utility has its own Phasor Data Concentrator (PDC) to
  • Aggregate/align data from various PMUs based on time tag

PDC / Vector Processor

PMU 1
PMU 2
PMU 3
Synchronized Measurements

- Measurements from each utility’s PDC is sent to the Central Facility:
  - Where the measurements are synchronized across utilities
Comparison Between SCADA and PMUs

• PMUs have much faster sampling rate:
Synchrophasor Definition

• Synchrophasor:
  • Time-tagged sequence phasor measured at different locations.
PMU Architecture

- A GPS receiver is used to time-stamp measurements:

Measurements from all PMUs will be synchronized
Measurement Synchronization

- It is achieved via:
  - 24 Satellites
  - 12 Hour Orbit Time
  - Signal: Position, Velocity, Time
  - Visibility:
    - 5 to 8 Satellites from
    - Any point at any time!
Measurement Synchronization

• Performance:

  • 95% Reliable
  • 100 nanosecond time accuracy
  • **Q:** Good enough?

• Positioning is not a concern in PMUs.
Preventing Blackouts

• An application of PMUs and Situational Awareness:
  • Quickly respond to emergencies
  • Prevent disturbance propagation
  • Planned islanding, if needed
  • Limited scope load shedding, if needed
  • Faster system restoration

• In general, we have no idea what happened after blackout.
Northeast Blackouts 2003

• Affected:
  
  • About **10 Million** People in Ontario, Canada
  
  • About **45 Million** People in 8 U.S. States

• Initiated in **Ohio** because of
  
  • A **device** and also **human error**.
  
  • A sequence of events finally led to the blackout.
Northeast Blackouts: Map of the Areas Affected

Some of the Major Cities Affected: New York, Toronto, Detroit, Cleveland, Ottawa
Northeast Blackouts: Map of the Areas Affected

- Video: http://www.youtube.com/watch?v=6nt0njgVmv4.

Downtown Toronto

Evening of August 14, 2003
Northeast Blackouts: Brief Timeline

• 12:15:00 EDT: Some error in **State Estimator** in Northern Ohio
  • 13:31:00 EDT: The Eastlake, Ohio generating plant **shuts down**
  • 16:05:57 EDT: Last point blackout could have been **prevented!**
  • 16:13:00 EDT: A total of **256 power plants** are offline
  • Restoration: It took up to **6 days** in some locations.
Northeast Blackouts: Brief Timeline

Rate of Line and Generator Trips During the Cascade
Northeast Blackouts: Brief Timeline

Map Legend: Probable Cause
- Configuration Isolated
- Under-Voltage
- Consequential Tripping
- Under-Frequency
- Operator Shutdown
- Not Determined
Northeast Blackouts: Brief Timeline

Map Legend: Probable Cause
- Configuration Isolated
- Under-Voltage
- Under-Frequency
- Consequential Tripping
- Operator Shutdown
- Not Determined

Timeline: 16:10:38.6 to 16:10:45.2
Northeast Blackouts: Brief Timeline

Map Legend: Probable Cause
- Configuration Isolated
- Under-Voltage
- Under-Frequency
- Operator Shutdown
- Consequential Tripping
- Not Determined
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- Operator Shutdown
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- Not Determined
PMU Measurements Could Warn Instability

August 14, 2003 Blackout

Phase Angles Diverged Prior To Blackout

Normal Phase Angle is approx. -25°
PMU Measurements Could Warn Instability

• We can also use analytical models to capture:
  • Dynamics of the phase angles and frequency.

• Usually we aim to reach linear models.

• The models can be used to
  • Analyze stability as we collect PMU readings
  • Find stability regions using simulations
Consider a network of $n$ generators connected to each other:

- Connections are through $m$ tie-lines, with $m \leq n \frac{(n-1)}{2}$

Example: with $n = 6$ generators and $m = 9$ tie-lines
• The internal voltage phasor of the \( i^{th} \) generator is denoted as:

\[
E_i \angle \delta_i, \quad i = 1, 2, \ldots, n.
\]

• For the link connecting \( p^{th} \) and \( q^{th} \) generators, impedance is:

\[
z_{pq} = r_{pq} + jx_{pq}.
\]

• And we have

\[
y_{pq} = \frac{1}{z_{pq}} = \frac{1}{r_{pq} + jx_{pq}}.
\]
• The dynamic electro-mechanical model of the $i^{th}$ generator:

\[
\dot{\delta}_i = \omega_i - \omega_s
\]

\[
2H \dot{\omega}_i = P_i - \sum_{k \in N_i} \left( \frac{E_i^2 r_{ik} - E_i E_k \sqrt{r_{ik}^2 + x_{ik}^2} \cos(\delta_i - \delta_k + \tan^{-1}\left(\frac{x_{ik}}{r_{ik}}\right))}{r_{ik}^2 + x_{ik}^2} \right)
\]

where

\[
\omega_s = 120\pi = \text{Nominal Angular Velocity at 60 Hz}
\]

\[
\omega_i = \text{Rotor Angular Velocity of Generator } i
\]
Dynamic Models

- A linear model around an initial equilibrium \((\delta_{i0}, \omega_{i0})\):

\[
\Delta \delta = \begin{bmatrix}
\Delta \delta_1 \\
\vdots \\
\Delta \delta_n
\end{bmatrix}, \quad \Delta \omega = \begin{bmatrix}
\Delta \omega_1 \\
\vdots \\
\Delta \omega_n
\end{bmatrix}.
\]

Assuming that a disturbance \(u\) enters the system at node \(j\):

\[
\begin{bmatrix}
\dot{\Delta \delta} \\
\dot{\Delta \omega}
\end{bmatrix} = \begin{bmatrix}
0 & I \\
L & 0
\end{bmatrix} \begin{bmatrix}
\Delta \delta \\
\Delta \omega
\end{bmatrix} + \begin{bmatrix}
0 \\
\varepsilon_j
\end{bmatrix} u
\]
• A linear model around an initial equilibrium \((\delta_{i0}, \omega_{i0})\):

\[
\begin{bmatrix}
\Delta \delta \\
\Delta \omega
\end{bmatrix} =
\begin{bmatrix}
0 & I \\
L & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \omega
\end{bmatrix} +
\begin{bmatrix}
0 \\
\varepsilon_j
\end{bmatrix} u
\]

where

\[I = n\text{-dimensional identity matrix}\]

\[\varepsilon_j = \text{A unit vector with all elements zero and the } j^{th} \text{ element is 1}\]
Dynamic Models

- A linear model around an initial equilibrium \((\delta_{i0}, \omega_{i0})\):

\[
\begin{bmatrix}
\dot{\Delta \delta} \\
\dot{\Delta \omega}
\end{bmatrix} =
\begin{bmatrix}
0 & I \\
L & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \omega
\end{bmatrix} +
\begin{bmatrix}
0 \\
\varepsilon_j
\end{bmatrix}u
\]

where

\[
L_{ii} = -\sum_{k \in N_i} \frac{E_i E_k}{\sqrt{r_{ik}^2 + x_{ik}^2}} \sin\left(\delta_{i0} - \delta_{k0} + \tan^{-1}\left(\frac{x_{ik}}{r_{ik}}\right)\right)
\]

\[
L_{ik} = \begin{cases} 
\frac{E_i E_k}{\sqrt{r_{ik}^2 + x_{ik}^2}} \sin\left(\delta_{i0} - \delta_{k0} + \tan^{-1}\left(\frac{x_{ik}}{r_{ik}}\right)\right) & \text{if } k \in N_i \\
0 & \text{otherwise}
\end{cases}
\]
• So far we have only modeled angle and angular velocity.

• Q: What if we measure voltage phasors using PMUs?

Measurement is done somewhere between two generators.

Ref: A. Chakrabortty et al.
• Voltage magnitude is obtained as

\[ V_{pq} = \sqrt{E_q^2 (1 - \alpha_{pq})^2 + E_p^2 \alpha_{pq}^2 + 2E_p E_q \alpha_{pq} (1 - \alpha_{pq}) \cos(\delta_p - \delta_q)} \]

where

\[ \alpha_{pq} = \frac{\bar{z}_{pq}}{z_{pq}} \]

\[ \bar{z}_{pq} = \text{Impedance from reference node to PMU location} \]
• The linearized model around \((\delta_{i0}, \omega_{i0})\) becomes:

\[
V_{pq} = \frac{a_{pq}(1-a_{pq})}{V_{pq}(\delta_{p0}, \delta_{q0})} E_p E_q \sin(\delta_{p0} - \delta_{q0}) \begin{bmatrix}
1 & -1 & 0 & 0
\end{bmatrix} \left[ \begin{array}{c}
\Delta \delta_p \\
\Delta \delta_q \\
\Delta \omega_p \\
\Delta \omega_q
\end{array} \right]
\]

where

\[
V_{pq}(\delta_{p0}, \delta_{q0}) = \text{Evaluation of Nonlinear Voltage Model at } \delta_{p0} \text{ and } \delta_{q0}
\]
Finally, the state space model becomes:

\[
\begin{bmatrix}
\dot{\Delta \delta} \\
\dot{\Delta \omega}
\end{bmatrix} =
\begin{bmatrix}
0 & I \\
L & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \omega
\end{bmatrix} +
\begin{bmatrix}
0 \\
\varepsilon_j
\end{bmatrix} u
\]

\[V_{pq} = C_{pq}
\begin{bmatrix}
\Delta \delta_p \\
\Delta \delta_q \\
\Delta \omega_p \\
\Delta \omega_q
\end{bmatrix}\]

The model can be used for:

- Stability Analysis
- System Identification
- Closed-loop controller / stabilizer design.
Region of Stability

• Using the non-linear/linear models and simulations:
  • We obtain regions for PMU readings that assure stability

• Contingency and security scenarios can also be considered.
Region of Stability

• Alarm is triggered as the trajectory approaches boundaries.

• Stability regions can also be used to visualize stability status.

• There can be several such two-dimensional regions.

• One challenge: where are the optimal locations for PMUs?
PMU Deployment Status

• PMU devices are available from many vendors:
  • ABB, Schweitzer, AMETEK, Arbiters, GE, Macrodyne, SEL

• New IEEE C37.118 standard has been approved.
  • Partly covered that in Topic 2.

• There are systems that are already installed and operating.
PMU Deployment Status

• Eastern Interconnection Phasor Project (EIPP):

- Number of utilities: 32
- Number of research organizations: 14
- Number of vendors: 27
- DOE investment in EIPP: $3 million (since 2002)
- Industry investment in EIPP: $15 million (5 to 1 leverage)
- Future DOE investment needed: $5 million (yearly)
- Number of years needed: 5 years

Source: EIPP
PMU Deployment Status

- Eastern Interconnection Phasor Project (EIPP):

  EIPP PMU Companies:
  - Ameren
  - AEP
  - ConEdison
  - Entergy
  - Excelon/ComEd
  - Excelon/PECO
  - First Energy
  - Hydro 1
  - LIPA
  - Manitoba Hydro
  - METC
  - Midwest ISO
  - NY ISO / NYPA
  - PPL Corp.
  - Southern Company
  - TVA

* Companies with PMUs Planned or In Service

Source: EIPP
PMU Deployment Status

• CCET Discovery Across Texas Project:

Source: CCET
PMU Deployment Status

• **FNET** (Frequency Monitoring Network) Project:
  
  • University of Tennessee
  
  • Virginia Tech

• They use a special type of PMU:
  
  • Frequency *Disturbance Recorder* (FDR)
PMU Deployment Status

• FDR measures
  
  • Measure frequency, phase angle, and voltage
    
    • Of the power system at ordinary 120 V outlets

• It is a single phase PMU.

• FDRs send data to the FNET servers over the Internet.

• Video: www.youtube.com/watch?v=9Vt2OlVoBJc (From 0:40)
• Locations of current FDRs installed:
• They have monitored frequency at some recent events:
  
  • Visualization of the Eastern Interconnection power system frequency before, during, and after a generator trip at the John Amos plant in Nitro, West Virginia. (8/6/2007).
    
    • Video: http://www.youtube.com/watch?v=f0rdFy1f4t4
  
  • They have also simulated some other major events:
    
    • Blackout of 2003 (8/14/2003).
      
      • Video: http://www.youtube.com/watch?v=eBucg1tX2Q4
PMU Deployment Status

• Link to FNET website:
  • http://www.tntech.edu/cesr/fnet
  • http://fnetpublic.utk.edu/

• Link to more captured events:
  • http://fnetpublic.utk.edu/sample_events.html

• Link to more simulations:
  • http://www.youtube.com/PowerITLabUTK

• M. Vaiman, M. Vaiman, S. Maslennikov, E. Litvinov, and X. Luo, "Calculation and Visualization of Power System Stability Margin Based on PMU Measurements", in Proc. of IEEE Smart Grid Communications Conference (Smart Grid Comm’10), Gaithersburg, MD, October 2010.