Capturing Real-Time Power System Dynamics: Opportunities and Challenges

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Frequency trending away from nominal requires tools capturing real-time dynamics

- Dynamic state estimation vs. traditional static state estimation
- Dynamic security assessment
- Dynamic model validation

(all identified as killer apps in NASPI phasor roadmap, [https://www.naspi.org/Badger/content/File/FileService.aspx?fileID=539](https://www.naspi.org/Badger/content/File/FileService.aspx?fileID=539))

<table>
<thead>
<tr>
<th>Year</th>
<th>Root Mean Square Error of Frequency Signal, Hz</th>
<th>Mean of Absolute Frequency Deviation, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>2,008</td>
<td>0.011</td>
<td>0.006</td>
</tr>
<tr>
<td>2,009</td>
<td>0.012</td>
<td>0.007</td>
</tr>
<tr>
<td>2,010</td>
<td>0.013</td>
<td>0.008</td>
</tr>
<tr>
<td>2,011</td>
<td>0.015</td>
<td>0.009</td>
</tr>
<tr>
<td>2,012</td>
<td>0.016</td>
<td>0.010</td>
</tr>
</tbody>
</table>

- Frequency trending away from nominal
- Dynamic state estimation vs. traditional static state estimation
- Dynamic security assessment
- Dynamic model validation

(Frequency Deviations Across New York - New Jersey, 8/14/03, by zip code)

Emergency situation

Normal operation

Frequency trending away from nominal requires tools capturing real-time dynamics
Dynamic paradigm for grid operation and planning

- **National Driver**: clean and efficient power grid as well as being affordable, reliable, and secure ➔ dynamic and fast

- **Technical Approach**: combine model prediction and measurement observations to determine where the grid is, where the grid is going, and where the grid could be (what-ifs).

![Diagram of dynamic states and time intervals](image)

- **Better Reliability**
- **Clean Energy Integration**
- **Better Asset Utilization**
Phasor measurement offers great opportunities for capturing dynamics

- Time-synchronized, high-speed measurement at 30 samples per second, able to capture the majority of grid dynamics

NASPI: [www.naspi.org](http://www.naspi.org)
General formulation of dynamic state estimation

- Two-step process
  - Prediction through model simulation
  - Correction using real-time phasor measurement
- Mathematical algorithms: Extended Kalman Filter, Unscented Kalman Filter, Ensemble Kalman Filter, Particle Filter, …

\[ x(k-1) \]

\[ z(k) \]

\[ x(k) \]

\[ x'(k) \]

\[ z = h(x, \alpha) + \varepsilon \]

“Prediction”
Dynamic Simulation
\[ \frac{dx}{dt} = f(x, \alpha) + v \]

Prediction Cycle
milliseconds

“Correction”
Measurement Eq’s
\[ z = h(x, \alpha) + \varepsilon \]

Correction Cycle
\(~1/30 \text{ second})
Excellent tracking with realistic evaluation conditions

- 3% measurement noise; 40 ms measurement cycle (phasor measurement)
- 5 ms interpolation cycle; modeling errors considered; unknown inputs; unknown initial states
Performance evaluation – computational speed (Ensemble Kalman Filter)

- Current codes scale to ~1,000 cores
- Current computational performance meets the real-time requirement for regional systems
- **Challenge**: real-time performance for interconnection-scale systems.

![Graph showing computational time per estimation step](image)

- Oct 2012: 16,072-Bus WECC
- June 2014: 1081-Bus Regional System
- 2017?: 10000 TeraFLOPS
- 30 ms
Performance evaluation – impact of non-Gaussian noises (Ensemble Kalman Filter)

- Non-Gaussian noise discovered in phasor measurements.
- Such non-Gaussian noises could result in large estimation errors.
- **Challenge**: new methods to accommodate non-Gaussian noises.
## Filtering technology comparison for dynamic state estimation

<table>
<thead>
<tr>
<th></th>
<th>Extended Kalman Filter</th>
<th>Unscented Kalman Filter</th>
<th>Ensemble Kalman Filter</th>
<th>Particle Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>The 2\textsuperscript{nd} best with 0% diverged</td>
<td>33% diverged</td>
<td>The best with 0% diverged</td>
<td>20% diverged (PF 2000)</td>
</tr>
<tr>
<td><strong>Efficacy of interpolation</strong></td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Number of samples needed</strong></td>
<td>None</td>
<td>Small</td>
<td>Medium</td>
<td>Large</td>
</tr>
<tr>
<td><strong>Sensitivity to missing data</strong></td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Sensitivity to outliers</strong></td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td><strong>Computation time (non-parallel)</strong></td>
<td>Shortest</td>
<td>Same order as EKF</td>
<td>longer than EKF</td>
<td>Same order as EnKF</td>
</tr>
</tbody>
</table>
Extending the formulation for dynamic model validation and calibration

- Treating parameters as augmented states
  - \( \frac{d\alpha}{dt} = g(x,\alpha) = 0 \)
- Dynamic states and parameters are estimated simultaneously, suitable for real-time applications

\[
\begin{align*}
\text{Prediction} & : 
\begin{align*}
& \text{Dynamic Simulation} \\
& \quad \frac{dx}{dt} = f(x,\alpha) + \nu \\
& \quad \frac{d\alpha}{dt} = g(x,\alpha)
\end{align*}
\end{align*}
\]

\[
\begin{align*}
\text{Correction} & : 
\begin{align*}
& \text{Measurement Eq's} \\
& \quad z = h(x,\alpha) + \varepsilon
\end{align*}
\end{align*}
\]

\( Q \)  \( R \)  \( z^{(k)} \)  \( x^{(k)},\alpha^{(k)} \)  \( x^{(k-1)},\alpha^{(k-1)} \)
Before calibration: Significant mismatch between simulation and measurement
Calibration of Generator Dynamic Model
(Data from August 18, 2002, 1500 MW Navajo units drop)

After calibration: model and measurement match.

- Inertia Constant
- Exciter Gain
- Real power (MW)
- Reactive power (MVar)

Inertia
Exciter Gain
Measurement
Model
Measurement
Model
Multi-Event Model Verification: good match across multiple events after calibration

Event 1: July 16 2002, 2588 MW RAS generation drop

Event 2: Verification (July 28 2003, 1252 MW Palo Verde #3 trip and 1500 MW of other generation loss)
Capturing dynamics is necessary because the power grid is trending to be more dynamic (frequency deviates from nominal more often with larger amplitude).

A dynamic paradigm is proposed to capture emerging dynamics and understand where the grid is, where the grid is going, and where the grid could be (what-ifs).

Phasor measurements offer opportunities for implementation with Kalman filters.

- Great performance for dynamic state estimation and dynamic model validation, ready for pilot testing and adoption.

Challenges remain in real-time computational performance and non-Gaussian noise impact.
References


Questions?