A Knowledge-based Approach to Situational Awareness for the Power Grid using Synchrophasors

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Agenda

- Introduction: Situational awareness for the power grid
- Brief history of wide-area measurements at Hydro-Québec (SMDA)
- Overview of Wide-Area Situational Awareness System (WASA)
- Advanced capabilities of WASA
- References
A knowledge-based approach to situational awareness (SA)

- **Definition of SA according to M. Endsley (1995)**
  - Perception of environment – e.g., monitoring real-time state of the grid
  - Comprehension of the environment – e.g., grid awareness
  - Projection of future status – e.g., early warning

- **Our approach combines an understanding of synchrophasor data and power system behavior with data analytics to give operators increased visibility into the real-time state of the grid**

- **Applies cognitive techniques**
  - Infer knowledge (e.g., about complex events) based on PMU measurements
  - Create abstraction model of granular sensor data reported by PMUs
  - Develop a cognitive model of the grid operator, engineer or analyst
Situational awareness for the power grid

- During 2012-2016, we developed a situational awareness system using a wide-area, *in situ* network of synchrophasors (WASA)

- But first, let’s review where it all began – SMDA. WASA was envisioned to be the future SMDA.
  - SMDA: Système de Mesure du Décalage Angulaire
  - HQ was the pioneer in angle shift measurement system (wide-area measurements)
## Hydro-Québec leadership in PMU space (1976-2004)

<table>
<thead>
<tr>
<th>Year (version)</th>
<th>Synchronizing Signal (Accuracy)</th>
<th># of PMUs</th>
<th>Rate (Hz)</th>
<th>Data concentrator features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976 (0.0)</td>
<td>LC (46 μs) – 1 degree electrical angle</td>
<td>2</td>
<td>1</td>
<td>Custom database</td>
</tr>
<tr>
<td>1981 (3.0)</td>
<td>GEOS</td>
<td>3</td>
<td>30</td>
<td>4000 records possible</td>
</tr>
<tr>
<td>1988 (4.0)</td>
<td>IRIG-B (20 μs)</td>
<td>4</td>
<td>60</td>
<td>1) Central unit on a HP-1000 computer. Visualization on a sun computer using a X-Windows based multi-users operating system 2) Voltage asymmetry computation 3) New “Raima” database with 10,000 records of angle and 600 records of voltage asymmetry</td>
</tr>
<tr>
<td>1991 (4.0)</td>
<td>IRIG-B (20 μs)</td>
<td>8</td>
<td>60</td>
<td>4 more PMUs</td>
</tr>
<tr>
<td>1995 (4.0)</td>
<td>IRIG-B (20 μs)</td>
<td>8</td>
<td>60</td>
<td>Computation of bus voltage harmonic content up to the 10th</td>
</tr>
<tr>
<td>1998 (4.1)</td>
<td>IRIG-B (20 μs)</td>
<td>8</td>
<td>60</td>
<td>Continuous record up to 6 months</td>
</tr>
<tr>
<td>2004 (5.0)</td>
<td>GPS (1 μs)</td>
<td>8 (10 in 2008)</td>
<td>60</td>
<td>Change from IREQ-made PMU to Macrodyne commercial PMU. Change from Raima to ORACLE database.</td>
</tr>
</tbody>
</table>

SMDA (version 5.0)

Acquisition Unit Administration and Monitoring
WASA system installed at IREQ

- **Advanced data concentrator features**
  - High-throughput, low-latency data acquisition using stream computing platform
  - Real-time event detection
  - Tools for visual analytics
    - Replay / comparison of events (voltage magnitude, frequency, phase angle charts)
    - Query engine to search for information based on time, event type, event sequence, event episode, etc.
    - High-level summarization of events and their statistics
  - Real-time correlation analysis and early warning
  - Deployment on software platform supporting analytics and optimization
    - Linux OS
    - InfoSphere Streams
    - Informix timeseries database

- **Integrated system that supports decision making from raw PMU data**
  - Current industry state-of-the-art is more focused on monitoring than decision-making
Advanced capabilities of WASA

1. Localize fault for a complex event by drilling down on PMU data
2. High-level summarization of grid data
3. Generate early warnings for geomagnetic disturbances (GMDs)
Capability 1 – Post-event fault localization in the control room

Leaf-level boxes in cognitive task analysis chart above are associated with user “actions” in WASA system.
Capability 1 – Search events

GIS Map View and Search Panel in WASA system
Capability 1 – Playback charts for a complex event

Ground truth: *loss of load* followed by *over-frequency*
Capability 1 – Adjust focus of attention

Slider window can be adjusted to shift focus of attend on increase in frequency (top) and sharp fluctuation in phase angle (bottom).
Capability 1 – Toggle PMU measurements to isolate behaviors
Capability 2 – High-level summarization of grid events

- Filter events
- What are low probability events during the year?
Capability 3 – Real-time prediction for geomagnetic disturbances (GMDs)

- Solar eruptions known as Coronal Mass Ejections (CMEs) can cause geomagnetic disturbances (GMDs)
- Electrically charged particles from CMEs may take a few hours or a few days to reach the earth and cause disruptions in the power grid
- Geomagnetic effects from CMEs are discernable in the power system as geo-magnetically induced currents or GIC
- Real-time alerting can provide early warnings ahead of significant impacts on the grid
Capability 3 – Real-time prediction for geomagnetic disturbances (GMDs)

• Utilities primarily rely on forecasted / actual values of magnetic activity (indices) but do not couple with grid activity automatically
• We bring in new data sources and correlate with PMU data, *relaxing the constraints of strict time alignment*
Capability 3 – Example model: correlating geomagnetic/electric and grid behaviors

Hypothesis: Geomagnetic/geoelectric field data are good predictors of GMD-related harmonics activity on the grid and can be used to alert operators in advance of large-scale events.

Even Harmonics vs. Time (30 mins)

Fourth Harmonics vs. Time (30 mins)
Capability 3 – Example model: using predictions to enable mitigating actions (cont.)

We find that $E_y$ is a good predictor of grid activity during a GMD.
Capability 3 – Learn associations across external data sources

- By discovering relationships between physical variables (features) from external sources of data relevant to GMDs that have different prediction latencies, we may be able to generate alarms earlier, giving the operator additional lead time to take mitigating actions.

- We map the timestamps of these features to GIC-related grid voltage distortion data processed from synchrophasor streams – this enables us to discover relationships between features that are relevant for predicting the effects of GMDs on the grid.

A high confidence rule between $x_i$ and $y_j$ affirms that the relationship is predictive of grid impact.

Capability 3 – Learn associations across external data sources (2)

- Start with grid voltage distortion event (target condition) with start time, $t_i$, (shown on right) representing time instant at which the even harmonic distortion ratio (EHD) exceeded the threshold (or GIC is detected).

- Add rows to table for time instants, $t_j$, such that $t_i - t_j \leq delay_1$, where $delay_1$ is the time lag for the GMD to impact the grid following its effect on the earth’s magnetic field.

- For each $t_j$, include corresponding magnetometer readings and ACE measurements for time instants, $t_k = t_j - TCME$. $TCME$ is an estimate of $delay_2$. $Delay_2$ measures the time between impact at the ACE satellites in $L1$ orbit and impact on the earth’s magnetic field. In practice, $delay_2$ ranges from 1-3 hours, an estimate of the time to complete the solar wind-magnetosphere coupling.
Take-aways …

- PMUs provide operators data, but they do not provide operators knowledge.
- Knowledge of the past (post-event analysis), present and future (real-time early warnings) enables better decision making.
- In addition, we use machine learning techniques to find richer relationships/patterns across multiple data sources (space weather) for robust GMD prediction.
References


PMU References


