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

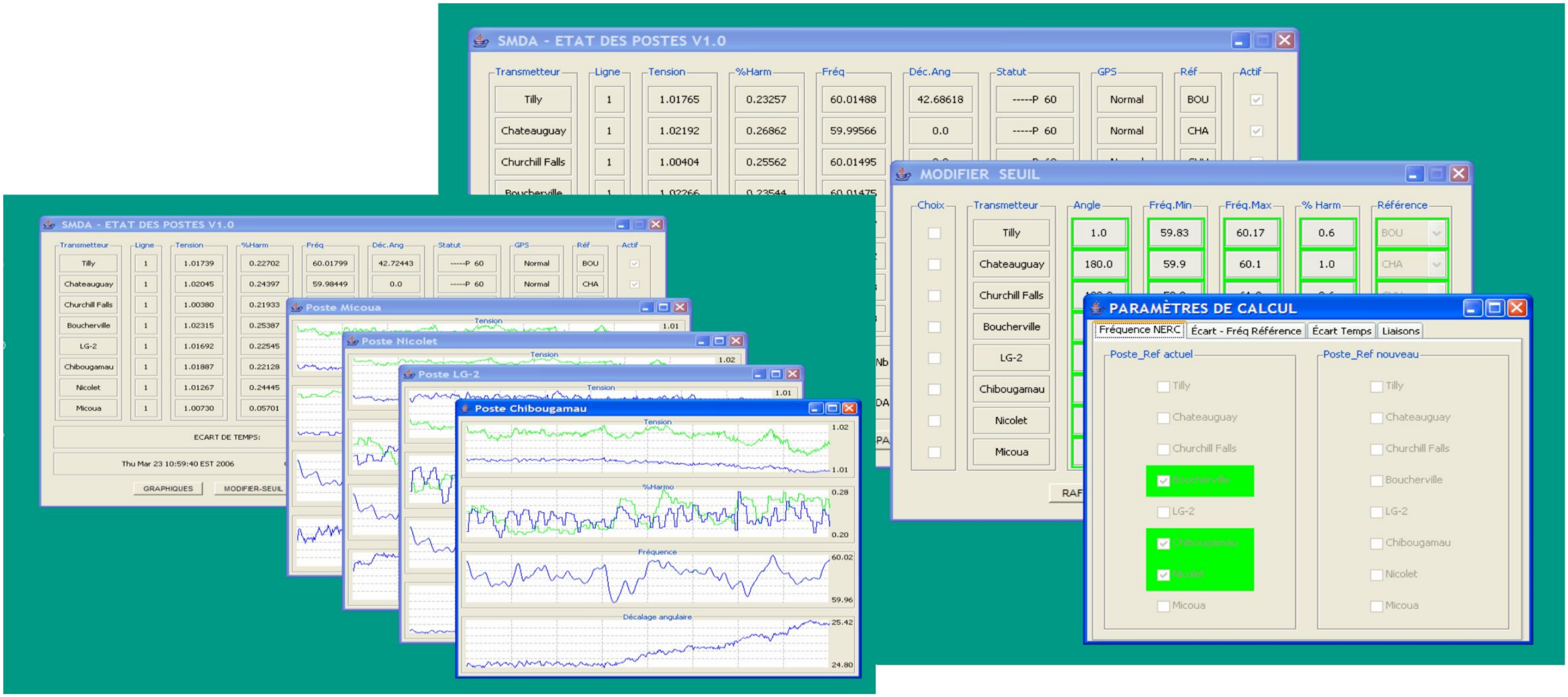
- **During 2012-2016, we developed a situational awareness system using a wide-area, *in situ* network of synchrophasors (WASA)**
- **But first, let’s review where it all began – SMDA. WASA was envisioned to be the future SMDA.**
  - SMDA: Système de Mesure du Décalage Angulaire
  - HQ was the pioneer in angle shift measurement system (wide-area measurements)

Hydro-Québec leadership in PMU space (1976-2004)

Year (version)	Synchronizing Signal (Accuracy)	# of PMUs	Rate (Hz)	Data concentrator features
1976 (0.0)	LC (46 µs) – 1 degree electrical angle	2	1	Custom database
1981 (3.0)	GEOS	3	30	4000 records possible
1988 (4.0)	IRIG-B (20 µs)	4	60	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
1991 (4.0)	IRIG-B (20 µs)	8	60	4 more PMUs
1995 (4.0)	IRIG-B (20 µs)	8	60	Computation of bus voltage harmonic content up to the 10th
1998 (4.1)	IRIG-B (20 µs)	8	60	Continuous record up to 6 months
2004 (5.0)	**GPS (1 µs)**	**8 (10 in 2008)**	**60**	**Change from IREQ-made PMU to Macrodyne commercial PMU. Change from Raima to ORACLE database.**

Table from: I. Kamwa, J. Beland, G. Trudel, R. Grondin, C. Lafond, and D. McNabb. “Wide-area Monitoring and Control: Past, Present, and Future,” in *Proceedings of the IEEE Power & Energy Society General Meeting*, Montreal, Quebec, July, 2006.

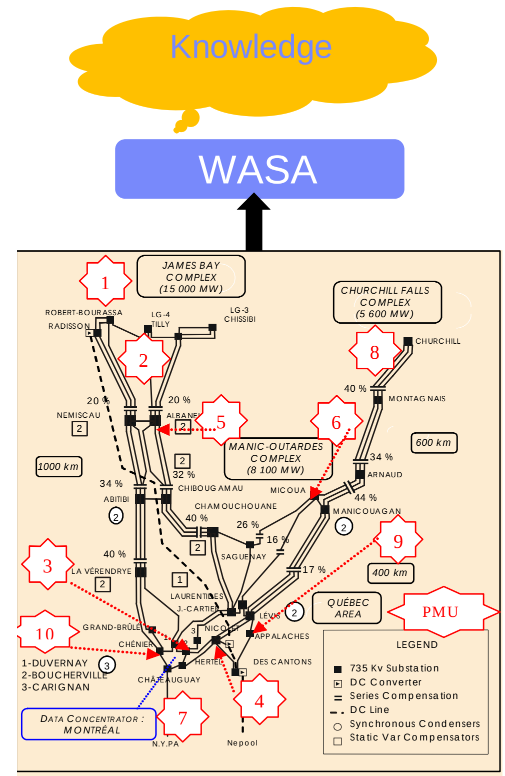
SMDA (version 5.0)



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

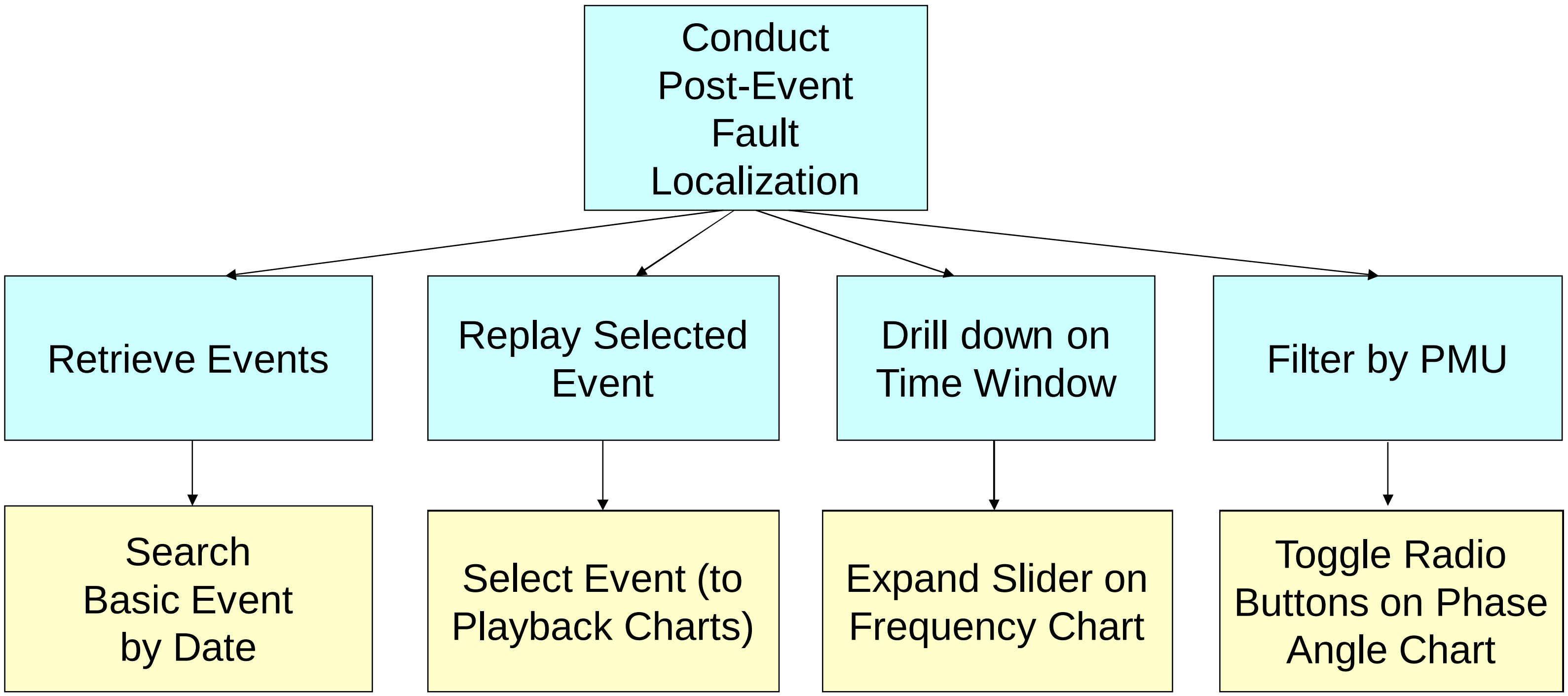


- **Integrated system that supports decision making from raw PMU data**
  - Current industry state-of-the-art is more focused on monitoring than decision-making

Advanced capabilities of WASA

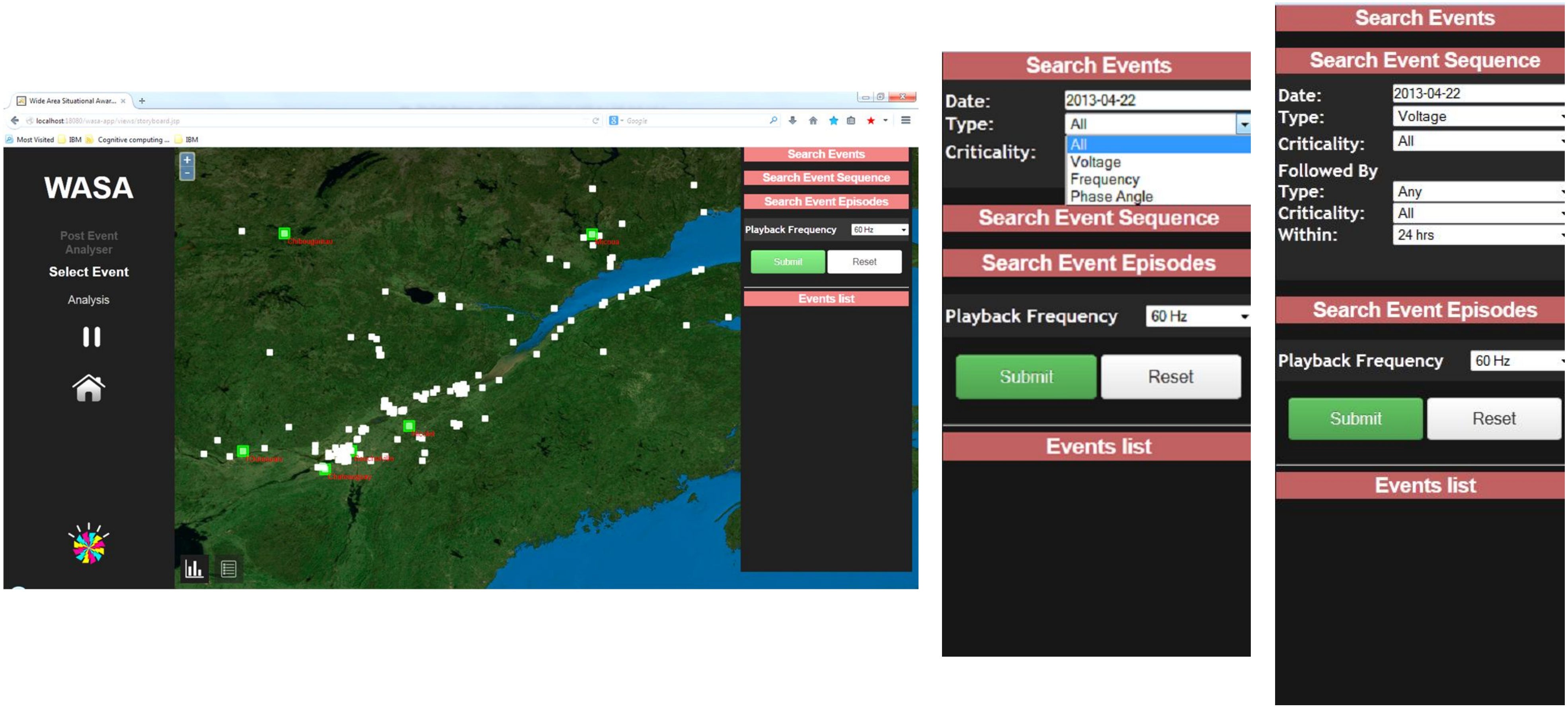
1. **Localize fault for a complex event by drilling down on PMU data**
2. **High-level summarization of grid data**
3. **Generate early warnings for geomagnetic disturbances (GMDs)**

Capability 1 – Post-event fault localization in the control room



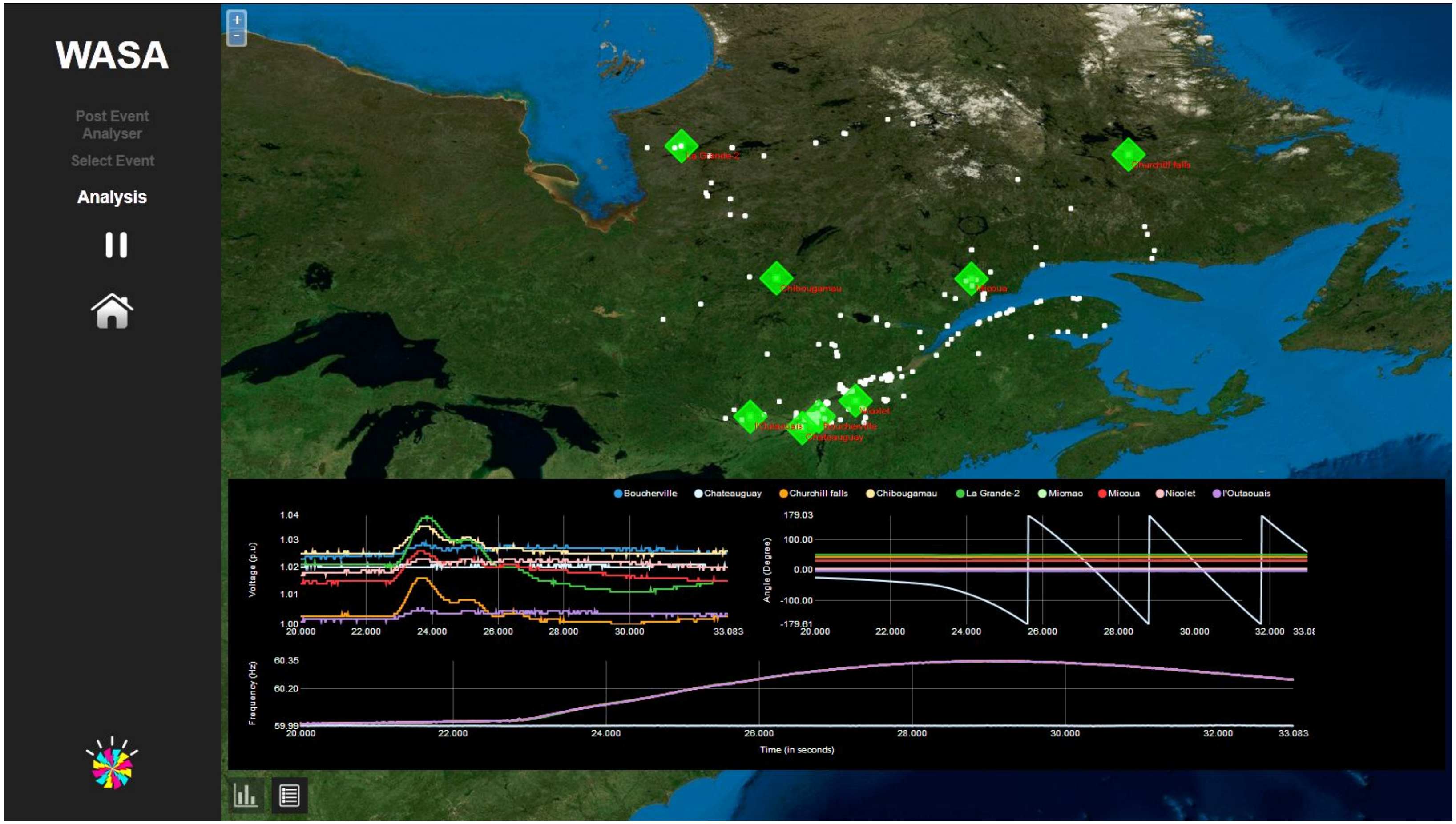
Leaf-level boxes in cognitive task analysis chart above are associated with user "actions" in WASA system.

Capability 1 – Search events



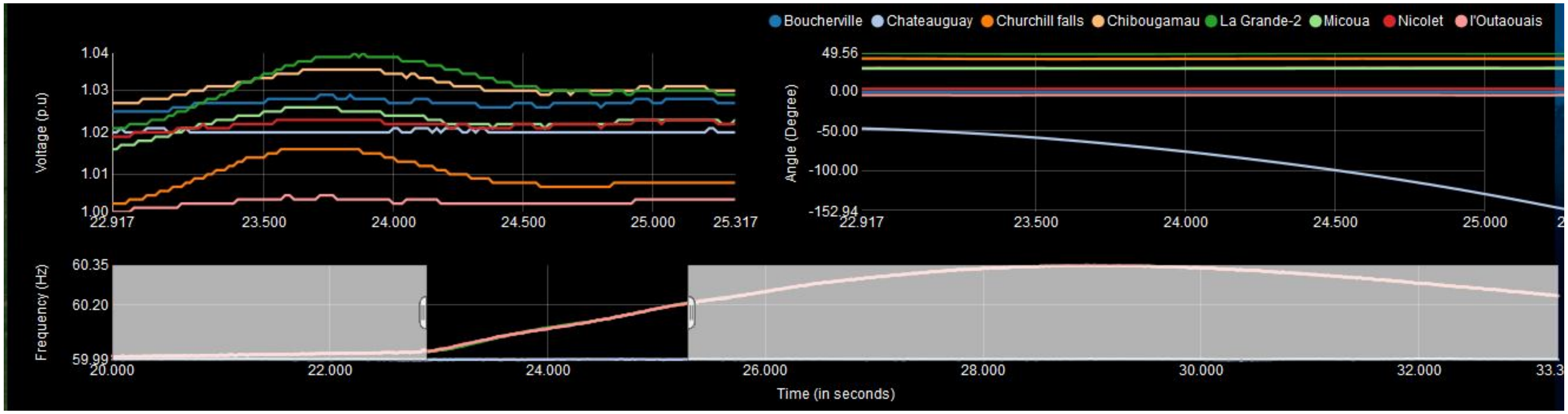
GIS Map View and Search Panel in WASA system

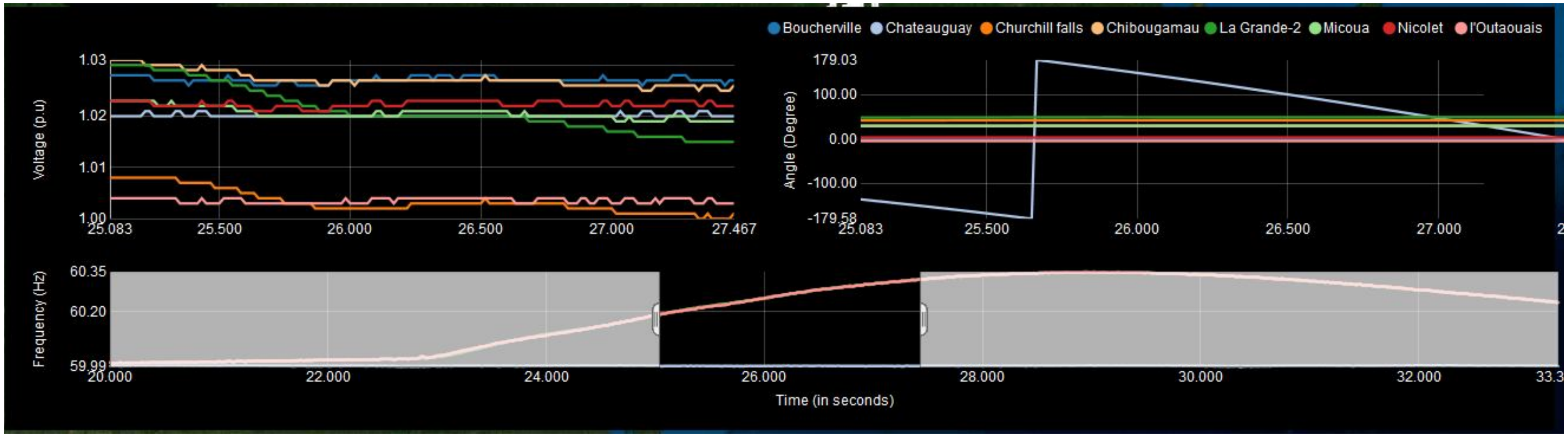
Capability 1 – Playback charts for a complex event



Ground truth: *loss of load* followed by *over-frequency*

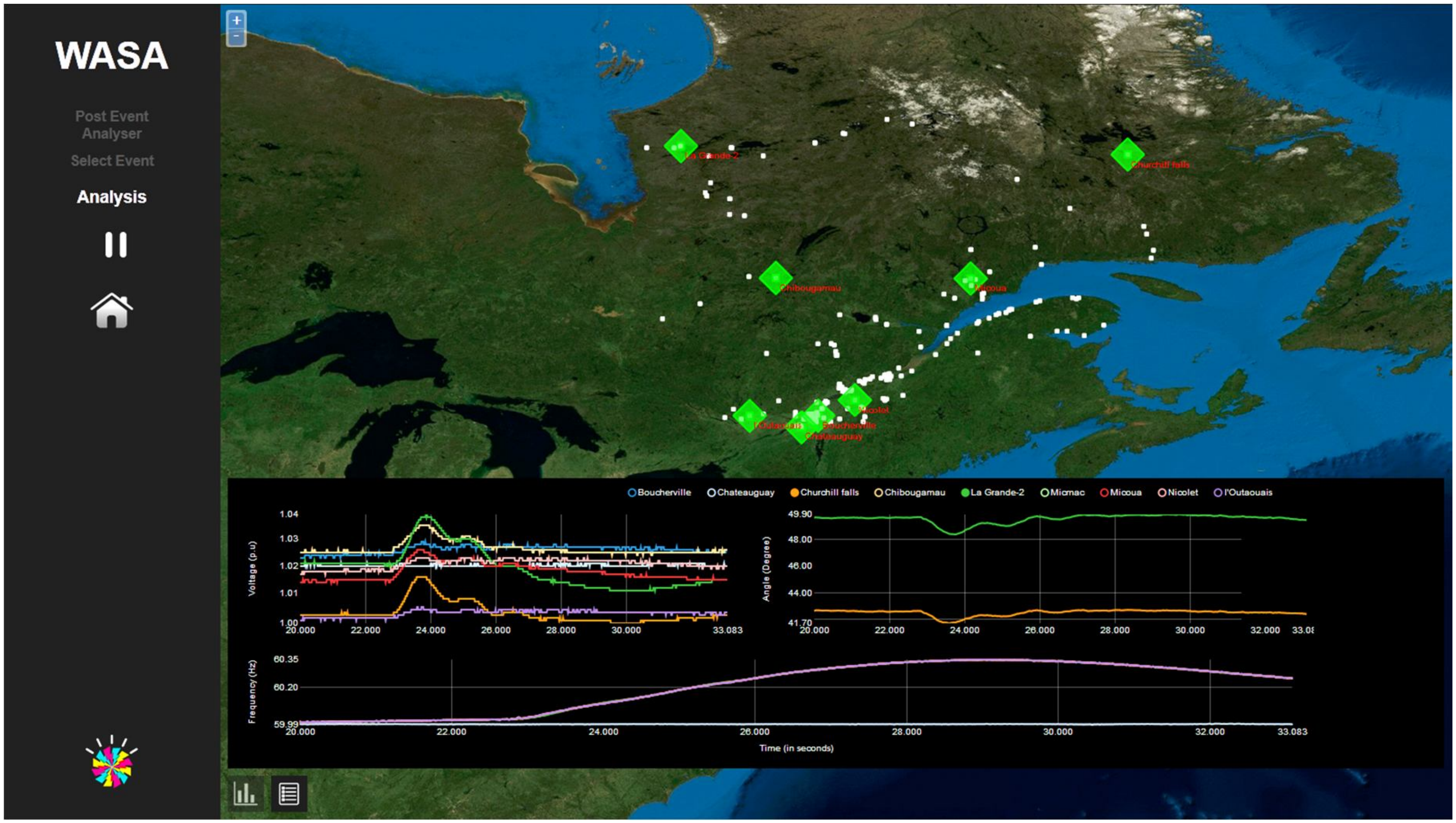
Capability 1 – Adjust focus of attention



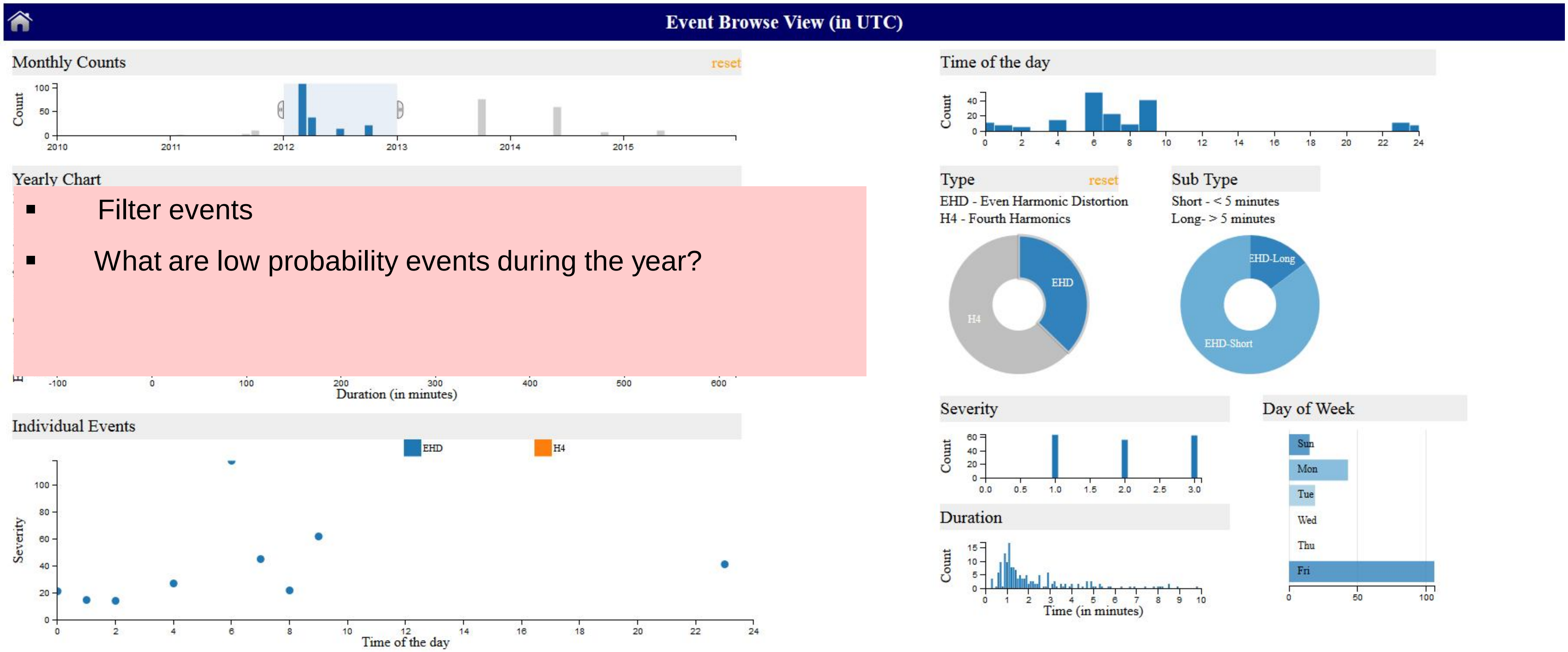


Slider window can be adjusted to shift focus of attend on increase in frequency (top) and sharp fluctuation in phase angle (bottom).

Capability 1 – Toggle PMU measurements to isolate behaviors



Capability 2 – High-level summarization of grid events



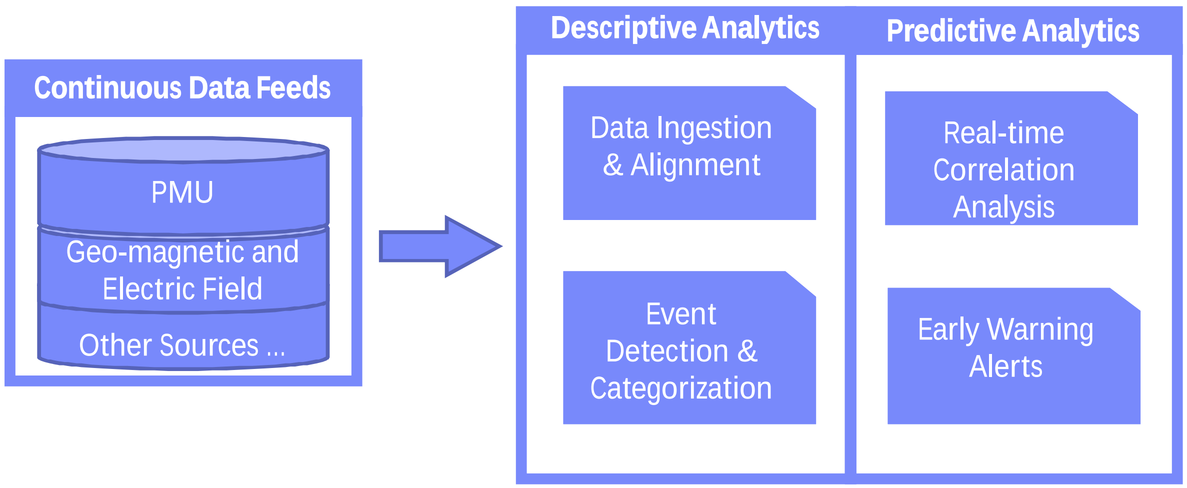
- Filter events
- What are low probability events during the year?

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)

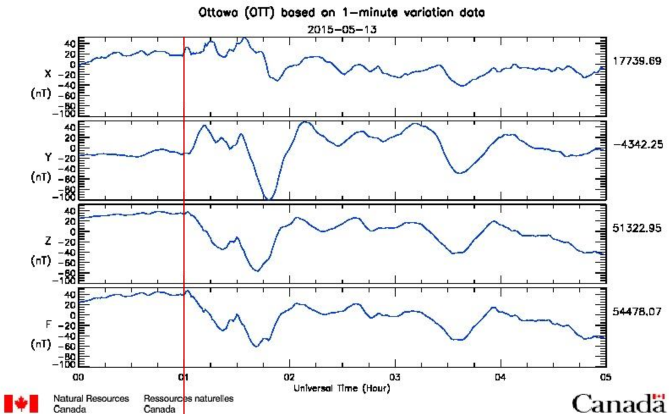
- **Utilities primarily rely on forecasted / actual values of magnetic activity (indices) but do not couple with grid activity automatically**
- **We bring in new data sources and correlate with PMU data, *relaxing the constraints of strict time alignment***



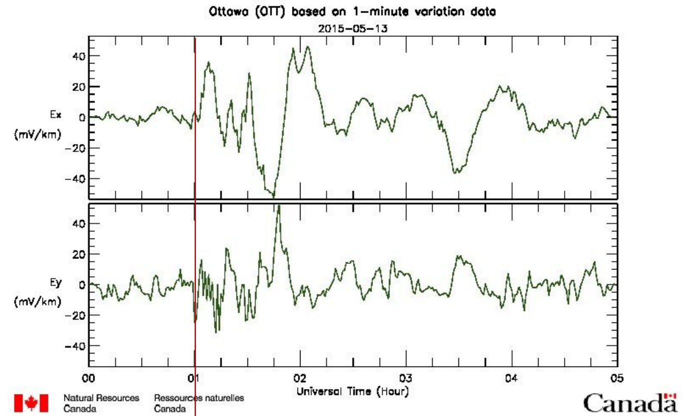
Hydro Québec IBM

Capability 3 – Example model: correlating geomagnetic/electric and grid behaviors

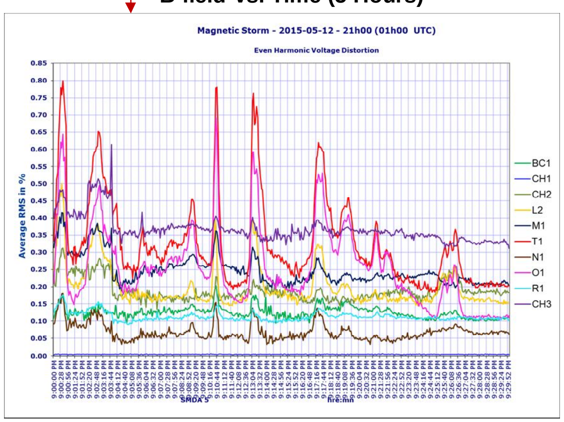
Hypothesis: Geomagnetic/geoelectric field data are good predictors of GMD-related harmonics activity on the grid and can be used to alert operators in advance of large-scale events



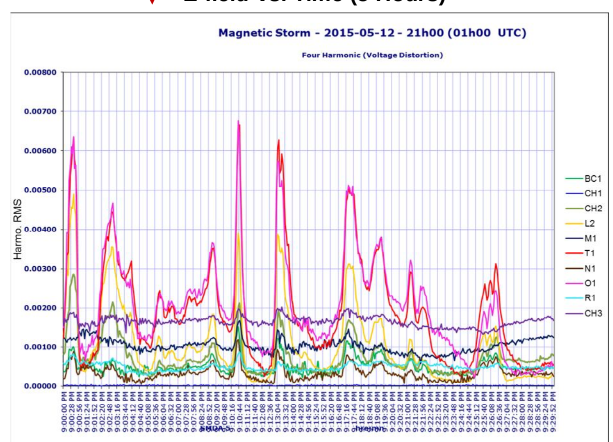
B-field vs. Time (5 Hours)



E-field vs. Time (5 Hours)

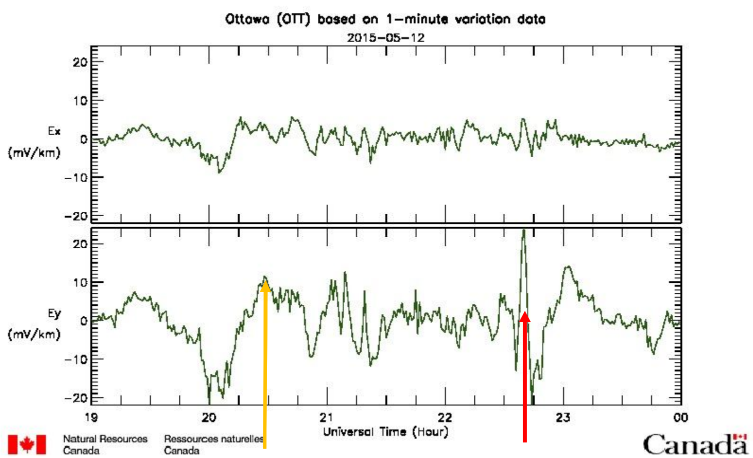


Even Harmonics vs. Time (30 mins)

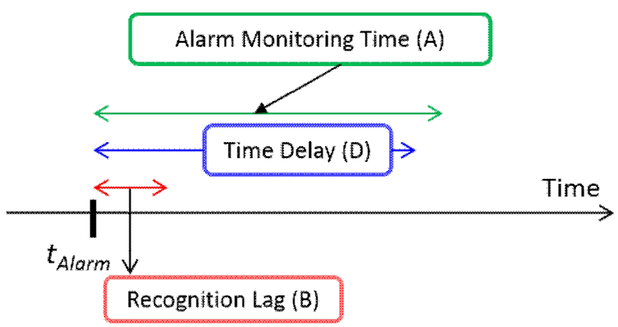


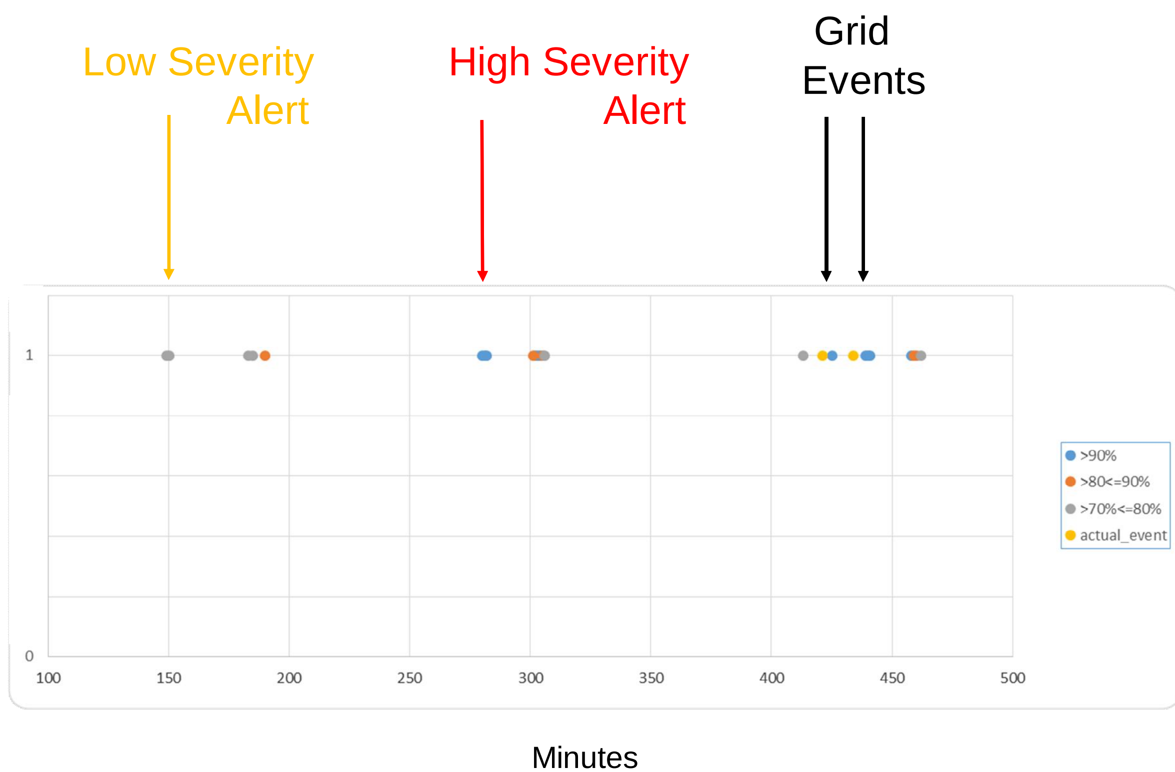
Fourth Harmonics vs. Time (30 mins)

Capability 3 – Example model: using predictions to enable mitigating actions (cont.)



Ey during Low & High Severity Alerts

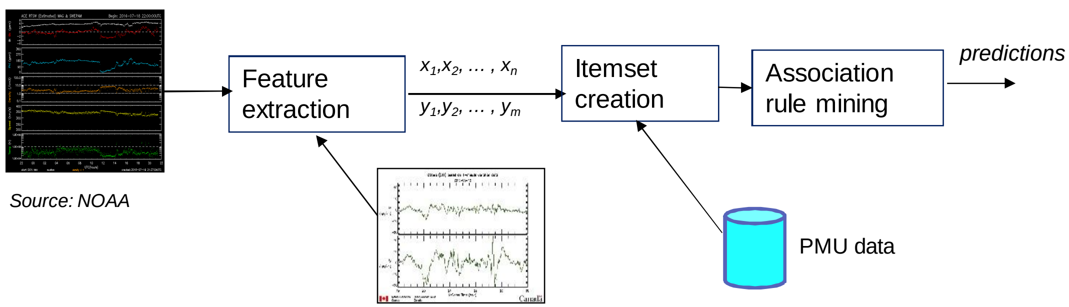




We find that Ey is a good predictor of grid activity during a GMD.

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**



Source: NOAA

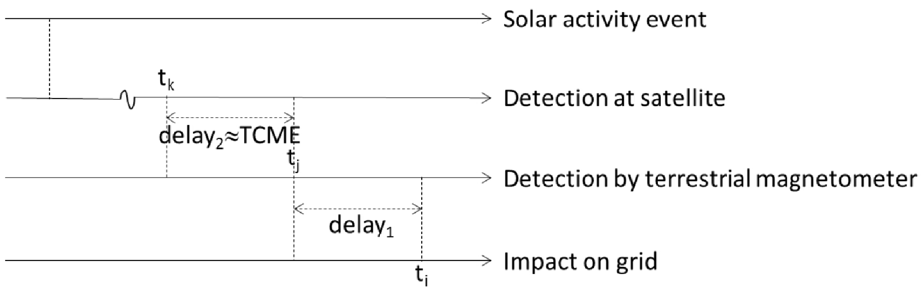
Source: Natural Resources Canada

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

C. Basu, M. Padmanaban, S. Guillon, L. Cauchon, M. De Montigny, I. Kamwa. Association Rule Mining to Understand GMDs and their Effects on Power Systems, *Proceedings of the IEEE Power & Energy Society General Meeting*, Boston, MA, July 2016..

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 $t_i - t_j <= delay_1$, 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**

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