RPM Prototype Preliminary Validation Results, User Interface, Deployment Plan and Field Test

By: Carlos Martinez – CERTS/ASR, Pete Sauer and Alejandro Dominguez-Garcia – University of Illinois
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Presentation Outline

• RPM Prototype Objectives

• Description of MISO Phasor Data Available for RPM Prototype

• Review CERTS Monitoring Applications Portfolio and Reliability Research as Leverages for RPM Portfolio

• Review Propose Model-Less Algorithms and 3 Performance Grid Metrics – Univ. of Illinois

• Review Prototype’s Algorithms and Metrics Preliminary Validations Results for “Normal” and Disturbance” Days - Univ. of Illinois

• Review, Discuss and Agree on Prototype Notifications and User Interface and Daily Reliability Performance Report

• Review Action Items, Deployment Schedules and Field Test
RPM Prototype Goals and Objectives

The objectives of the Reliability Performance Monitoring (RPM) project are: research, functional specification, deployment, and field test of a prototype real time monitoring application using model-less algorithms producing integrated Load-Generation control and Grid Reliability performance metrics, presented via consistent user notifications and a graphic interface, running with MISO phasor data in MISO phasor infrastructure.
<table>
<thead>
<tr>
<th>Line</th>
<th>Transmission Line Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DSY5 - Roseau (Forbes)</td>
</tr>
<tr>
<td>2</td>
<td>DSY230 - Laverendrye (11)</td>
</tr>
<tr>
<td>3</td>
<td>DSY230 - Laverendrye (15)</td>
</tr>
<tr>
<td>4</td>
<td>Arpin - Rocky Run</td>
</tr>
<tr>
<td>5</td>
<td>Goodland - Morrison Ditch</td>
</tr>
<tr>
<td>6</td>
<td>Montgomery - Labadie #4</td>
</tr>
<tr>
<td>7</td>
<td>Gibson - Merom</td>
</tr>
<tr>
<td>8</td>
<td>AB Brown - Gibson</td>
</tr>
<tr>
<td>9</td>
<td>Bloomington - Worthington</td>
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<td>10</td>
<td>Worthington - Merom</td>
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<tr>
<td>11</td>
<td>Hanna - Stout</td>
</tr>
<tr>
<td>12</td>
<td>Hanna - Sunnyside</td>
</tr>
<tr>
<td>13</td>
<td>Sunnyside - Gwynnville</td>
</tr>
</tbody>
</table>

Note: Expected number of MISO critical flowgates 3 to 5 times in 3 years
MISO 345KV BPS Area Used for Prototype Preliminary Validations
RPM Prototype – Part of CERTS Portfolio of Reliability Monitoring Applications

**PRIMARY CONTROL MONITORING**
- Intelligent Alarms Application (IA)
- Frequency Monitoring and Analysis Application (FMA)
- Automatic Reliability Reports Application (ARR)
- Short Term Alarms
- Daily and Monthly Monitoring Reports
- Seasonal and Yearly Trending Reports

**SECONDARY CONTROL MONITORING**
- Intelligent Alarms Application (IA)
- DCS Alarms
- ACE-Frequency Monitoring (10, 30, 60 Minutes)
- CPS-BAAL Monitoring (30 Min, 24 Hours, 30 Days)
- Situational Awareness (Trace and Alarm Dashboard)

**TERTIARY CONTROL MONITORING**
- Intelligent Alarms Application (IA)
- Long Term Alarms
- Inadvertent Application (Inadvertent)
- Area Interchange Error Application (AIE)

**TIME ERROR CONTROL/CORRECTION MONITORING**
- Time Error Control, Correction
- Intelligent Alarms Application (IA)
- ARR Application

**LOAD-GENERATION-GRID ADEQUACY PERFORMANCE**
- G-ARR Project
- MISO Prototype
- FERC Prototype

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Performance Metrics and Process to Produce RPM Reports

**Controls**
- **Performance Metrics**
  - Primary Control Performance (Frequency Response)
  - Secondary Control Performance (AGC)
  - Tertiary Control Performance (Reserves Mgmt.)

**Monitoring Displays and Reports**
- ARR Reports
  - Daily
  - Monthly
  - Seasonal
  - Annual

**Current Users**
- Prototype for production since 2009
- Currently 54 users including NERC, FERC, DOE Staff, Subcommittees and Management

**Reliability Adequacy and Performance Monitoring**
- **Load-Generation Phase**
- **Transmission Phase**
  - Phase-1 Pre-Contingency State (COMPLETED)
  - Phase-2 Post-Contingency State

**Transmission States**
- Phase-1 Pre-Contingency State (COMPLETED)
- Phase-2 Post-Contingency State

**Performance Metrics**
- Phase-Angle Stability Power Transfer Limit
- Voltage Stability Power Transfer Limit
- Thermal Power Transfer Limit
- Data Confidence Bands for Each Metric

**Apply Research**
- MISO Hosting
  - For Validate Research Algorithms and Findings
  - Future Prototype Specification and Testing
Describe Model-Less Algorithms and Propose 3 Performance Metrics for MISO
Phasor Data Requirements

- The set of measured quantities include
  - Line-to-line voltages at both ends of the line
  - 3-phase complex power flowing into both ends of the line
- Measured quantities are sampled ten times per second
- Pseudo-measurements of line currents are obtained from the relation between complex power, voltage, and current
- Least Squares Errors (LSE) estimation is used to obtain per-second estimates of measurements and pseudo-measurements
- Since the system is at off-nominal frequency, phasor measurements rotate at a speed equal to the difference between the actual system frequency and the nominal frequency
  - To compensate for this effect, voltage estimates are redefined by defining the angle on one of the line ends to be zero and adjusting all other angles accordingly
Per-Second Voltage Estimate

- Phasor voltages measured on ends 1 and 2:
  \[
  \bar{V}_{1j} = V_{1j} \angle \theta_{1j} \\
  \bar{V}_{2j} = V_{2j} \angle \theta_{2j}
  \]
  where \( j = 1, 2, \ldots, N \) indexes the samples taken every second

- Per-second voltage and estimate:
  \[
  \hat{V}_{1\phi}[i] = \frac{\sum_{j=1}^{N} V_{1\phi}[i, j]}{N}, \quad \hat{\theta}_{1\phi}[i] = \frac{\theta_{1\phi}[i]}{N} - \frac{\pi}{6},
  \]
  \[
  \hat{V}_{2\phi}[i] = \frac{\sum_{j=1}^{N} V_{2\phi}[i, j]}{N}, \quad \hat{\theta}_{2\phi}[i] = \frac{\theta_{2\phi}[i]}{N} - \frac{\pi}{6},
  \]
  where voltage magnitudes are line-to-neutral

- A Similar calculation is conducted for the currents.
Stability limits

For Stability limits, it is necessary to obtain an estimate of the angle-across-system

- The angle-across-system can be calculated after obtaining two external system equivalents as seen from both ends of the monitored transmission line

These external equivalents are two simple per-phase Thevenin equivalents, where it is assumed that

- The Thevenin impedance is purely imaginary (resistance neglected)
- The magnitude of the Thevenin voltage source is known and equal to the nominal voltage of the line monitored
Thevenin Parameter Estimation

- Let $E_1$ and $E_2$ denote the Thevenin voltages on ends 1 and 2 of the line respectively, and let $\delta_1$ and $\delta_2$ be the Thevenin voltage angles.
- Let $X_1$ and $X_2$ be the corresponding Thevenin impedances.
- Per-second estimates can be obtained by solving:

$$A_1[i] \cdot \hat{X}_1[i]^2 + B_1[i] \cdot \hat{X}_1[i] + C_1[i] = 0,$$
$$A_2[i] \cdot \hat{X}_2[i]^2 + B_2[i] \cdot \hat{X}_2[i] + C_2[i] = 0,$$

where

$$A_1[i] = \hat{I}_{1\phi}[i]^2 - \hat{I}_{1\phi}[i-1]^2,$$
$$B_1[i] = 2\hat{I}_{1\phi}[i]\hat{V}_{1\phi}[i]\sin(\hat{\theta}_{1\phi}[i] - \hat{\gamma}_{1\phi}[i]) - 2\hat{I}_{1\phi}[i-1]\hat{V}_{1\phi}[i-1]\sin(\hat{\theta}_{1\phi}[i-1] - \hat{\gamma}_{1\phi}[i-1]),$$
$$C_1[i] = \hat{V}_{1\phi}[i]^2 - \hat{V}_{1\phi}[i-1]^2,$$

$$A_2[i] = \hat{I}_{2\phi}[i]^2 - \hat{I}_{2\phi}[i-1]^2,$$
$$B_2[i] = 2\hat{I}_{2\phi}[i]\hat{V}_{2\phi}[i]\sin(\hat{\theta}_{2\phi}[i] - \hat{\gamma}_{2\phi}[i]) - 2\hat{I}_{2\phi}[i-1]\hat{V}_{2\phi}[i-1]\sin(\hat{\theta}_{2\phi}[i-1] - \hat{\gamma}_{2\phi}[i-1]),$$
$$C_2[i] = \hat{V}_{2\phi}[i]^2 - \hat{V}_{2\phi}[i-1]^2.$$
Reliability Measures Definition

- Let $\delta_{12}^{\text{max}}$ be the maximum angle-across-system that ensures small-signal stability.

- A per-second stability margin index ($i$ indexes seconds) can be defined as:

$$L^s[i] = \frac{\delta_{12}^{\text{max}} - \hat{\delta}_{12}[i]}{\delta_{12}^{\text{max}}}.$$ 

- These per-second indices are the basis for defining stability margin reliability measures. For a one-hour period:
  - Normalized smallest angle-across-system margin
    $$H^s = \max_i \{L^s[i]\}, \quad i = 1, 2, \cdots, 3600,$$
  - Average angle-across-system margin
    $$AVG_1^s = \frac{1}{3600} \sum_{i=1}^{3600} L^s[i] = \frac{\delta_{12}^{\text{max}} - \frac{1}{3600} \sum_{i=1}^{3600} \hat{\delta}_{12}[i]}{\delta_{12}^{\text{max}}}.$$ 

- Similar measures can be defined for thermal ratings and voltage bounds.
Preliminary Test Environment and Data

1. MISO Line-4, STA1 and STA2

2. MISO 24-Hours of 30 Sample/Second Phasor Data for 08/17/11 – Normal Operations Day

3. MISO 24-Hours of 30 Samples/Second Phasor Data for 03/02/12 – Disturbance Day
MODEL AND METRICS VALIDATION
USING 08/17/11 DATA
“NORMAL OPERATIONS DAY”
System Angle Difference Using PMU Data for 8/17/11 – Normal Day
Angle Across System Stability Margin - 08/17/11
Voltage Largest Deviation Reliability Measure 08/17/11

Voltage Largest Deviation Reliability Measure - 8/17/2011

Plot Area
FREQUENCY AND VOLTAGE ALARMS
IDENTIFICATION CRITERIA
UNSING 03/02/12 DATA
“DISTURBANCE DAY”
Frequency Events Identification Criteria Event for Event on 03/02/12 at 14:53 in Eastern

A frequency event is detected, captured and archived if during a 15-second rolling window the frequency jumps beyond a pre-defined threshold for each Interconnection.
STA1 Voltage–Current 24-Hour Profile Using Phasor 03/02/12 Data – Disturbance Day
STA1 Voltage-Current 10-Minute Profile Using Phasor 03/02/12 Data
STA1 Voltage-Current 15-Second Profile Using Phasor 03/02/12 Data

A voltage event is detected, captured and archived if during a XX-second rolling window the voltage in “critical stations” jumps beyond pre-defined YY -thresholds.
PROPOSE PROTOTYPE NOTIFICATIONS AND USER INTERFACE
Propose RPM Prototype Notifications and User Interface

Objective: Monitor frequency, voltage and stability in an \textit{integrated} manner, using \textit{consistent} notifications, \textit{simple} graphical visualizations, \textit{model-less} algorithms and \textit{phasor} measurements

Target Users: MISO Reliability Coordinators

Identify and Archive: a) Frequency Events b) Voltage Events and c) Angle-Across-System Alarms using NERC & CERTS criteria from research

Broadcast above Alarms with Performance Report attached with the latest 24 hours of data at 1-minute resolution

Create the 24 Hour Performance Report with largest Frequency and Voltage event’s data/plots, and broadcast it automatically

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DAILY AND ON-DEMAND RELIABILITY REPORT
DAILY RELIABILITY PERFORMANCE REPORT

1. INTRODUCTION
The objective of this report is to provide a daily summary of load-generation control and Grid reliability performance for the MISO bulk Power System (BPS) using phasor measurements. The MISO daily report presents:

- Largest Frequency and Voltage Event of the Day:
  - Frequency-Time profile for the largest frequency event of the day
  - Estimation of Frequency Response and key parameters for largest frequency event
  - Voltage-Time profile for the largest voltage event of the day
  - Estimation of Voltage and key parameters for largest voltage event
- Grid Adequacy Performance Section:
  - Summary table with largest stability, voltage and thermal margins for key transmission lines
  - Statistical performance boxplot charts for the voltage and current profiles at key transmission lines.

2. LARGEST FREQUENCY AND VOLTAGE EVENTS OF THE DAY

2.1 Largest Frequency Event Data - 1 Second Frequency Time Graph
The frequency for this event dropped 0.065Hz (point A - point C) and stabilized (point B) in 21 seconds.

2.2 Largest Frequency Event Data - Estimated Frequency Response
The event reached a lowest frequency of 59.942 Hz at point C and starting returned to normal in about 21 seconds.

3. MISO GRID ADEQUACY PERFORMANCE

3.1 Summary Table with Largest Stability, Voltage and Thermal Margin for Key Transmission Lines
The summary table below shows the MISO transmission lines with the most critical and risky margins during the last 24 hours.

<table>
<thead>
<tr>
<th>MISO Grid Performance Lines</th>
<th>MISO Transmission Line</th>
<th>ANGLE MARGIN</th>
<th>VOLTAGE MARGIN</th>
<th>THERMAL MARGIN</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.309</td>
<td>0.718</td>
<td>NA</td>
<td></td>
<td></td>
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<tr>
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<td>0.718</td>
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<td>0.718</td>
<td>NA</td>
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</tr>
</tbody>
</table>

3.2 Statistical Performance Boxplot Chart for the Voltage and Current Profiles at Key Transmission Lines
The boxplot show the voltage and current distribution for each hour of the day.
Next Action Items for Deployment at MISO of RPM Prototype

- CERTS – Complete model/metrics validation using 03/02/12 phasor data – “Disturbance Day”

- CERTS – Tune model, metrics and thresholds for MISO, using phasor data for Eastern 2011 five largest frequency events, and five most critical lines from MISO list of 13 lines

- MISO to Review CERTS Prototype Functional Specification and continue and complete Prototype deployment

- CERTS to prepare and submit Prototype Field Test plan

- CERTS-MISO Field Test execution

- CERTS Final Report
# RPN Prototype Deployment at MISO

## Plan and Schedule

<table>
<thead>
<tr>
<th>No.</th>
<th>Deployment Activity</th>
<th>Est. Comp. Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CERTS - Presentation of Prototype preliminary validation results at MISO</td>
<td>03/22/2012</td>
</tr>
<tr>
<td>2</td>
<td>CERTS - Complete Prototype validations results using 03/02/12 phasor data</td>
<td>04/13/2012</td>
</tr>
<tr>
<td>3</td>
<td>MISO-Review Prototype Functional Spec. and give feedback to CERTS</td>
<td>04/18/2012</td>
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<tr>
<td>4</td>
<td>CERTS- Calibrate Prototype models, metrics and thresholds using phasor data for 5 largest Eastern frequency events and 5 MISO critical lines MISO – Verify Prototype final models and results</td>
<td>05/26/2012</td>
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<td>5</td>
<td>MISO – CERTS Continue and complete Prototype Deployment</td>
<td>??/??/2012</td>
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<td>6</td>
<td>CERTS – MISO Define and Create Prototype Field Trial plan</td>
<td>06/15/2012</td>
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<td>7</td>
<td>CERTS-MISO – Execute Field Trial</td>
<td>07/27.2012</td>
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<td>8</td>
<td>CERTS – MISO Final Report, Conclusions, Recommendations</td>
<td>09/14/2012</td>
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