*Consortium for*
*Electric*
*Reliability*
*Technology*
*Solutions*

**Reliability Performance Monitoring (RPM) Prototype**

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

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Carmel, Indiana, March 22, 2012

# *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

# *MISO BPS Transmission Lines with Phasor Measurements at Both Ends*

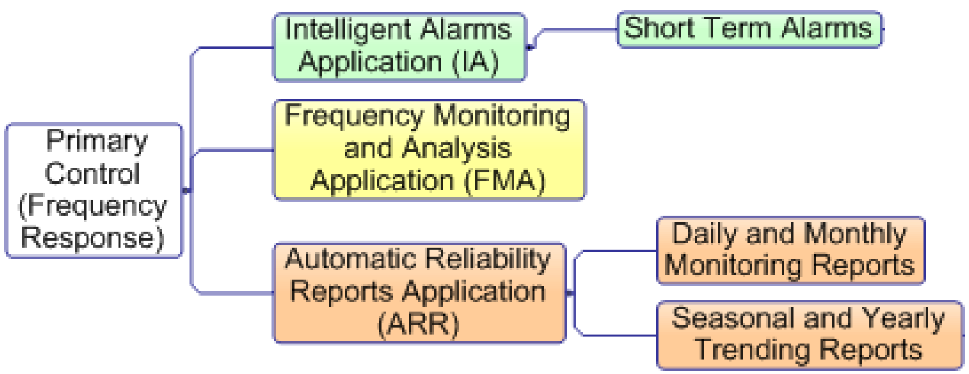
| Line | Transmission Line Name |
|---|---|
| 1 | DSY5 - Roseau (Forbes) |
| 2 | DSY230 - Laverendrye (11) |
| 3 | DSY230 - Laverendrye (15) |
| 4 | Arpin - Rocky Run |
| 5 | Goodland - Morrison Ditch |
| 6 | Montgomery - Labadie #4 |
| 7 | Gibson - Merom |
| 8 | AB Brown - Gibson |
| 9 | Bloomington - Worthington |
| 10 | Worthington - Merom |
| 11 | Hanna - Stout |
| 12 | Hanna - Sunnyside |
| 13 | Sunnyside - Gwynnville |

Note: Expected number of MISO critical flowgates 3 to 5 times in 3 years

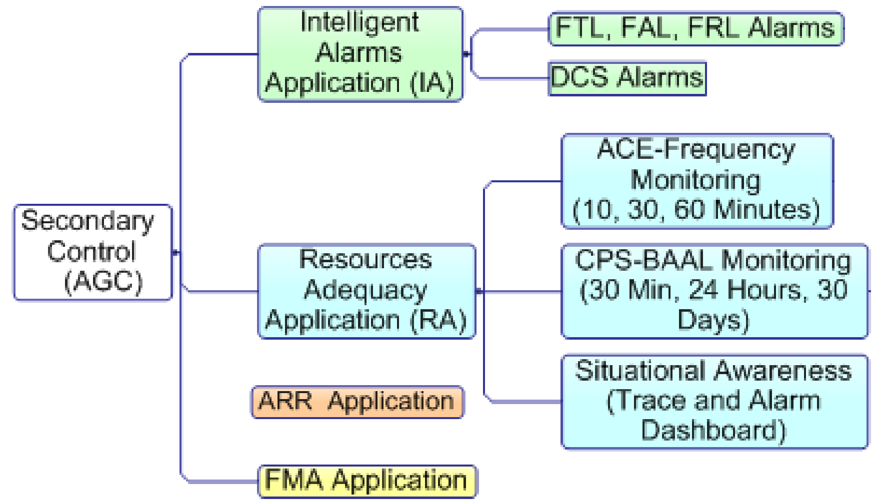
# *MISO 345KV BPS Area Used for Prototype Preliminary Validations*

# RPM Prototype – Part of CERTS Portfolio of Reliability Monitoring Applications

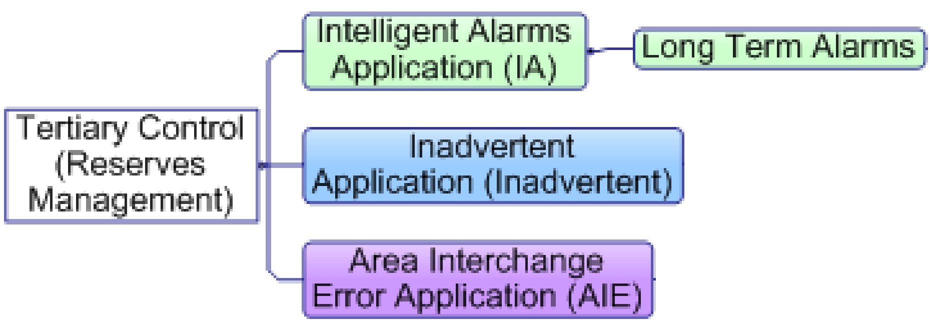
## PRIMARY CONTROL MONITORING



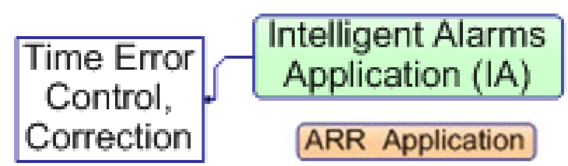

## SECONDARY CONTROL MONITORING



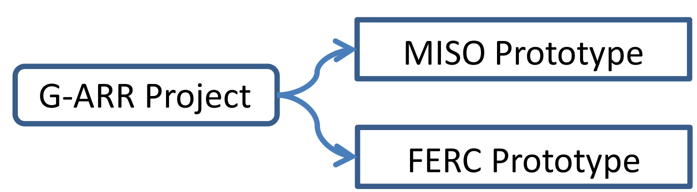

## TERTIARY CONTROL MONITORING



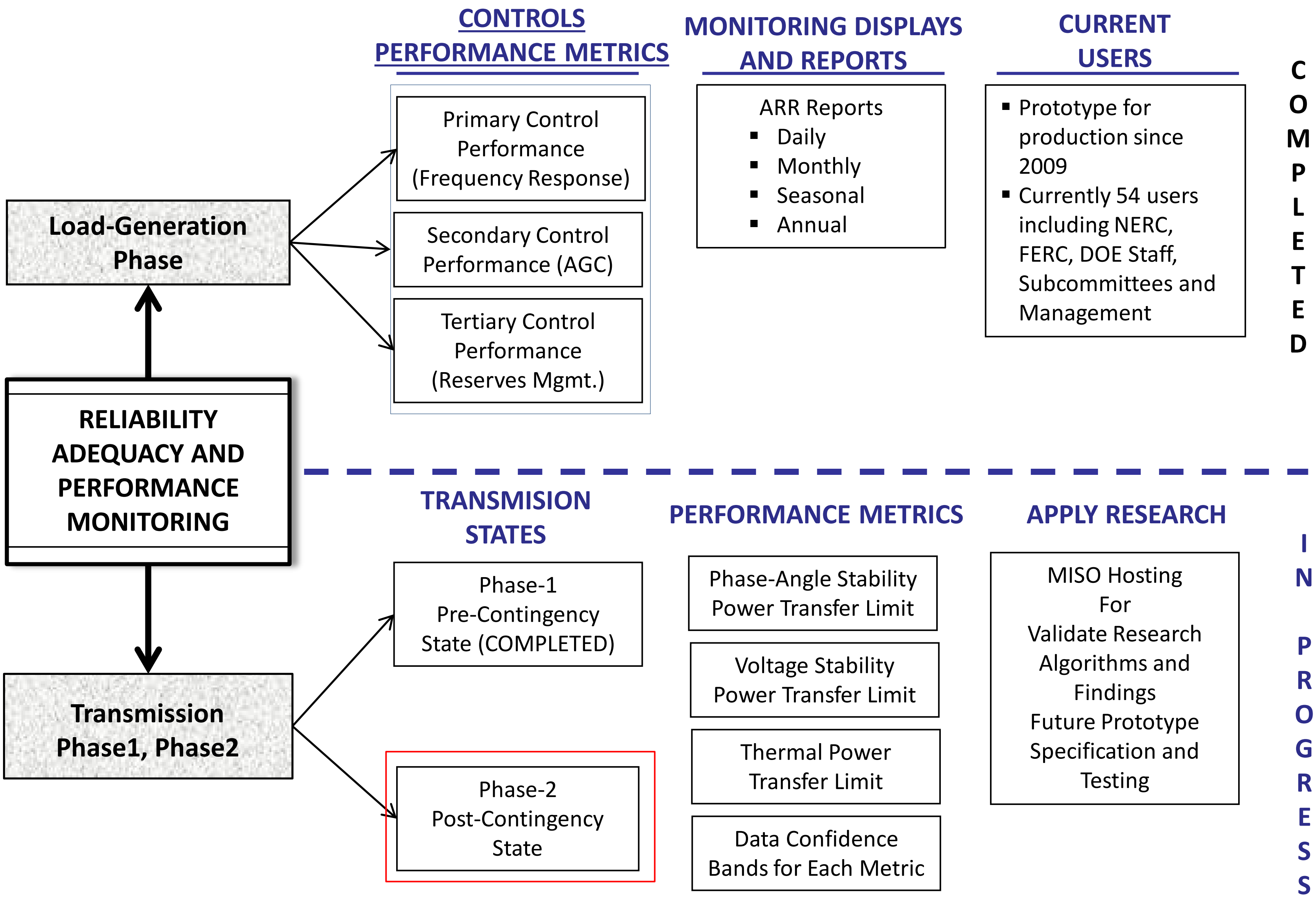

## TIME ERROR CONTROL/CORRECTION MONITORING




## LOAD-GENERATION-GRID ADEQUACY PERFORMANCE



# Performance Metrics and Process to Produce RPM Reports



# *Describe Model-Less Algorithms and Propose 3 Performance Metrics for MISO*

# Phasor Data Requirements

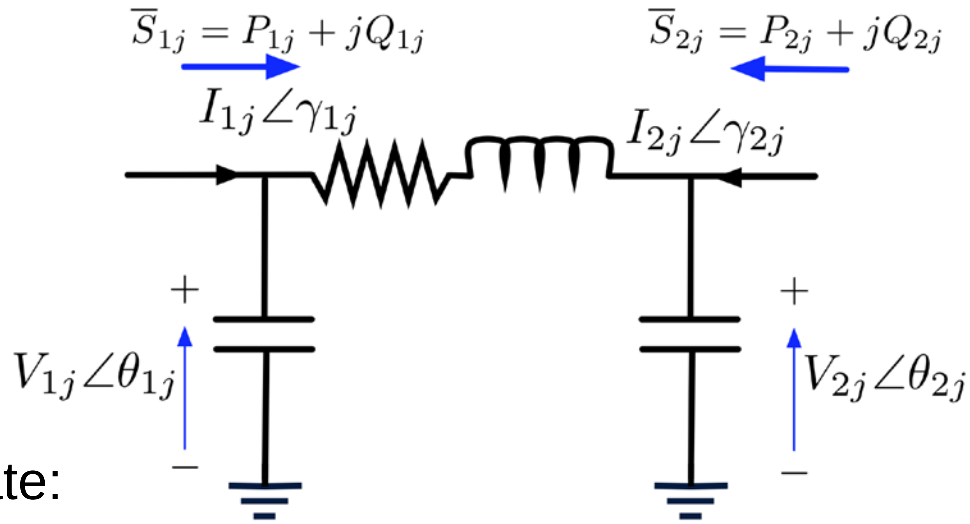
- The set of measured quantities include
  - Line-to-line voltages at both ends of the line
  - 3-phase complex power flowing into both ends of the line
- Measured quantities are sampled ten times per second
- Pseudo-measurements of line currents are obtained from the relation between complex power, 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:

$$\overline{V}_{1j} = V_{1j}\angle\theta_{1j}$$
$$\overline{V}_{2j} = V_{2j}\angle\theta_{2j}$$

where $j=1,2,\ldots,N$ indexes the samples taken every second



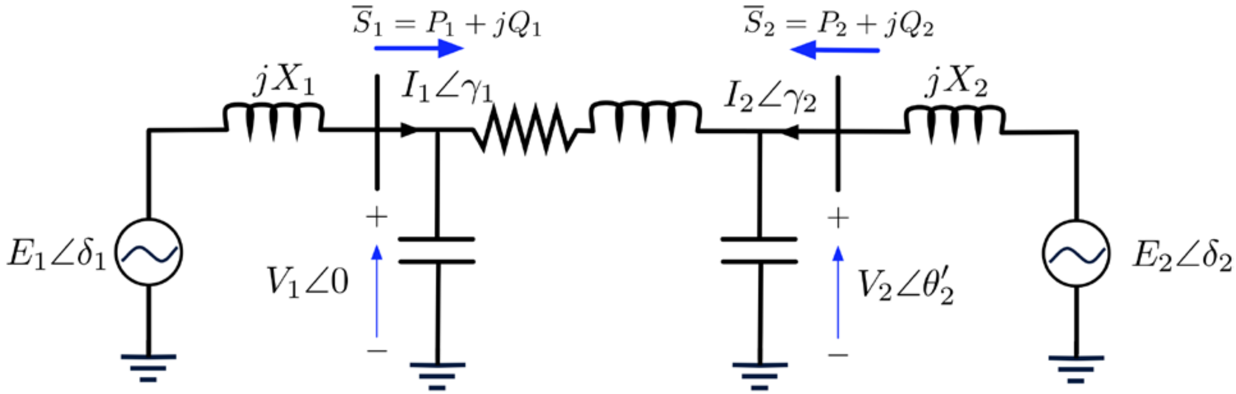

- Per-second voltage and estimate:

$$\hat{V}_{1\phi}[i] = \frac{\sum_{j=1}^{N} V_{1\phi}[i,j]}{N}, \quad \hat{\theta}_{1\phi}[i] = \frac{\sum_{j=1}^{N} \theta_1[i,j]}{N} - \frac{\pi}{6},$$
$$\hat{V}_{2\phi}[i] = \frac{\sum_{j=1}^{N} V_{2\phi}[i,j]}{N}, \quad \hat{\theta}_{2\phi}[i] = \frac{\sum_{j=1}^{N} \theta_2[i,j]}{N} - \frac{\pi}{6}.$$

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 $\delta_{12}^{max}$ be the maximum angle-across-system that ensures small-signal stability
- A per-second stability margin index ($i$ indexes seconds) can be defined as:

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

- These per-second indices are the basis for defining stability margin reliability measures. For a one-hour period:
  - Normalized smallest angle-across-system margin

$$H^s = \max_i \{L^s[i]\},\ i = 1, 2, \cdots, 3600,$$

  - Average angle-across-system margin

$$AVG_1^s = \frac{1}{3600} \sum_{i=1}^{3600} L^s[i] = \frac{\delta_{12}^{max} - \frac{1}{3600} \sum_{i=1}^{3600} \hat{\delta}_{12}[i]}{\delta_{12}^{max}}.$$

- Similar measures can be defined for thermal ratings and voltage bounds

# *Preliminary Test Environment and Data*

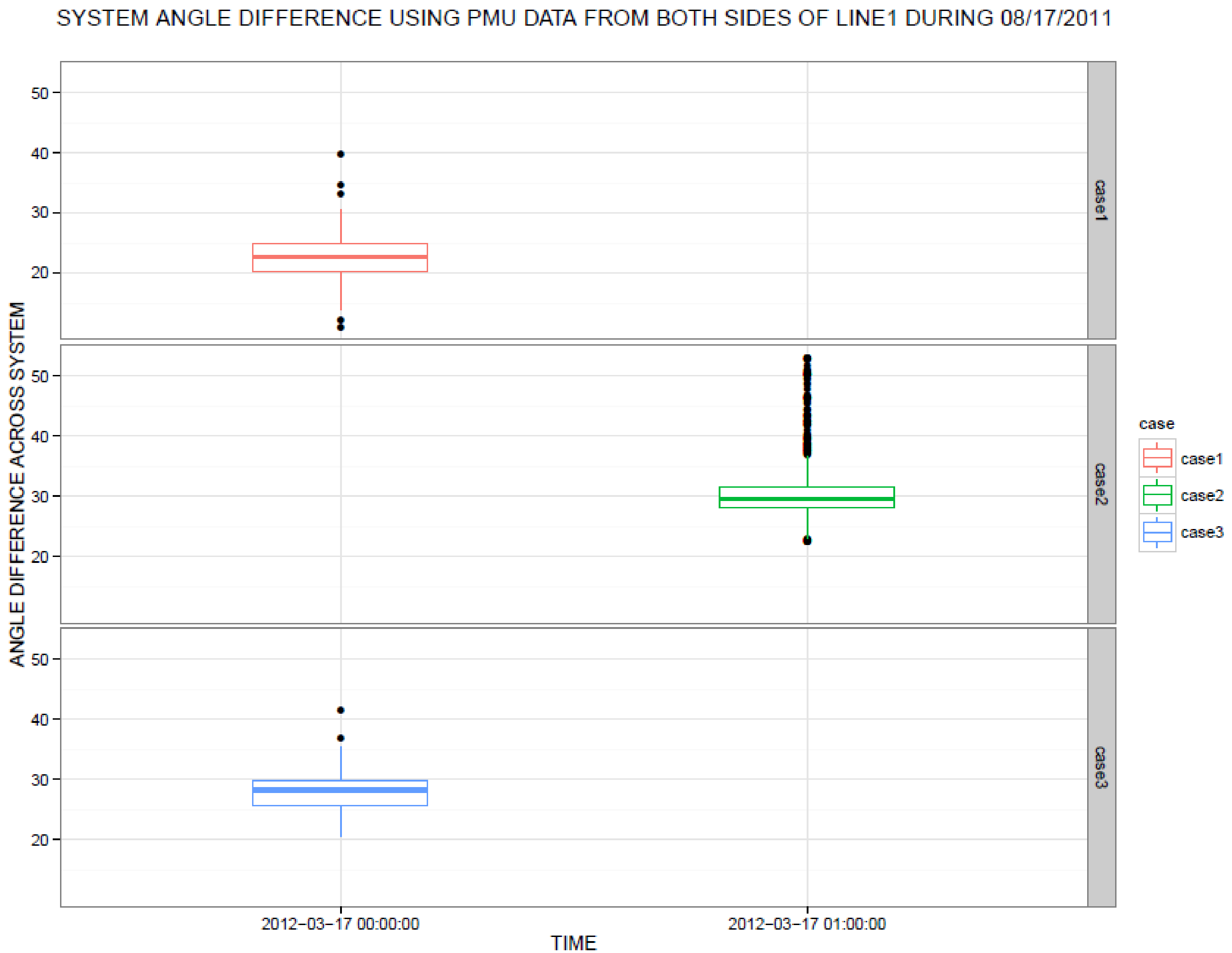
1. MISO Line-4, STA1 and STA2

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

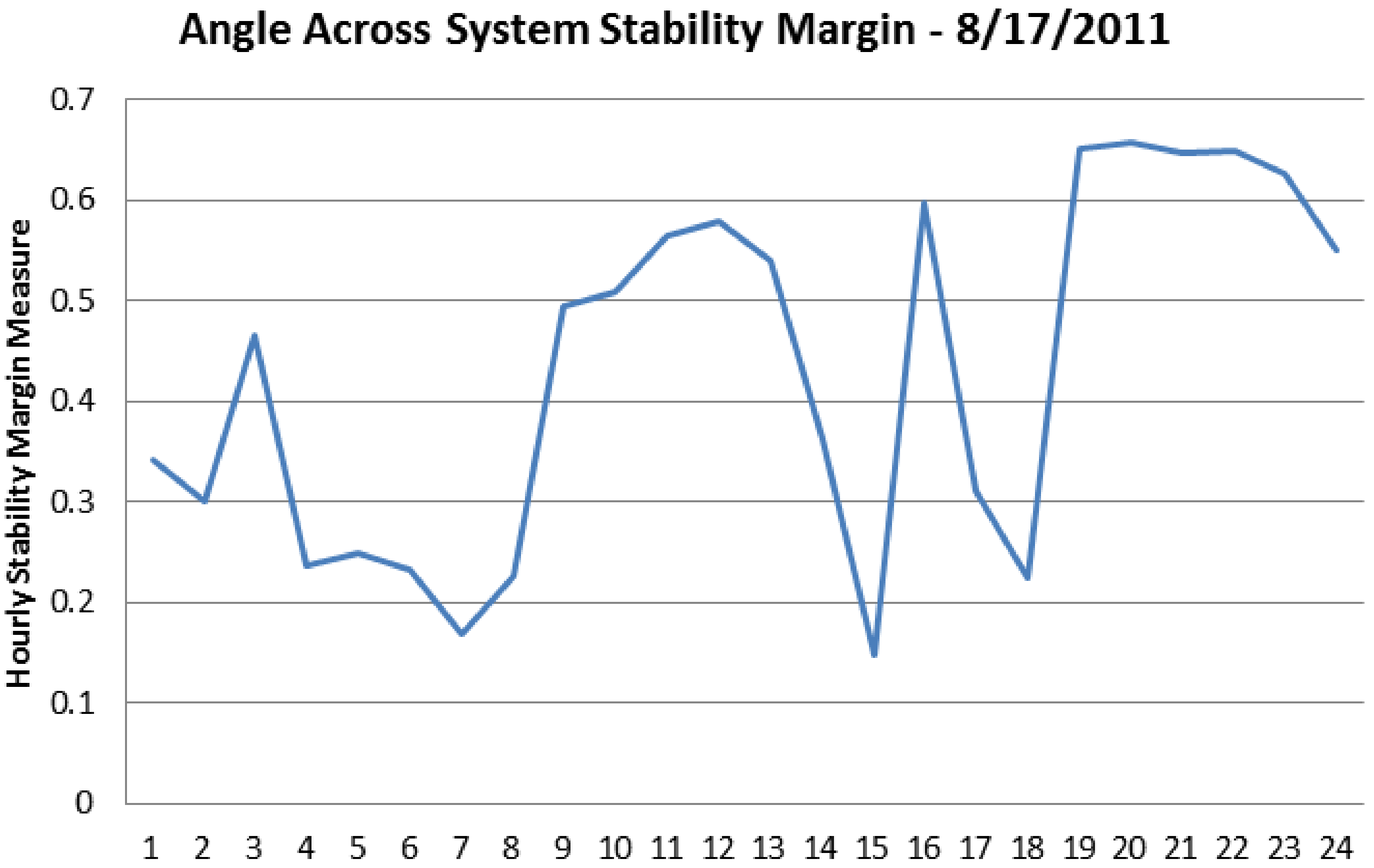
3. MISO 24-Hours of 30 Samples/Second Phasor Data for 03/02/12 – Disturbance Day

# *MODEL AND METRICS VALIDATION USING 08/17/11 DATA "NORMAL OPERATIONS DAY"*

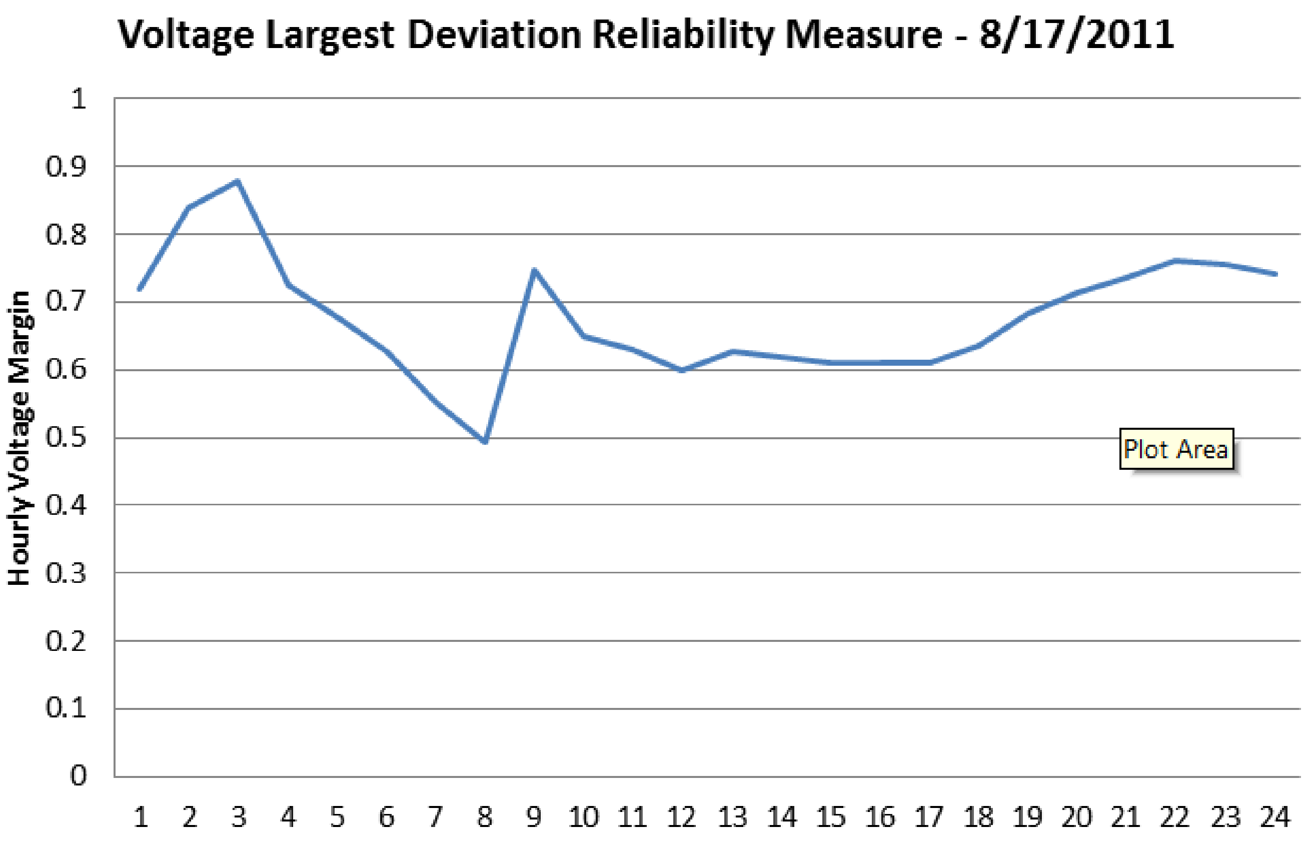
# System Angle Difference Using PMU Data for 8/17/11 – Normal Day



# *Angle Across System Stability Margin - 08/17/11*



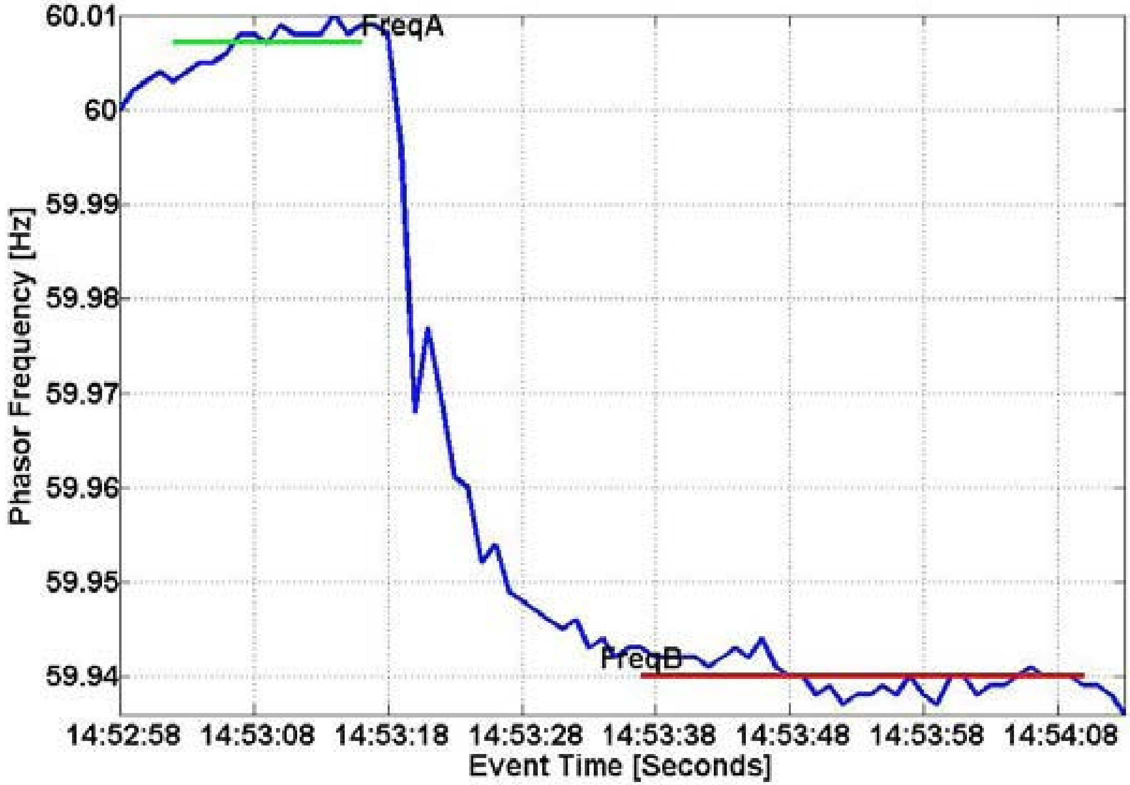
# *Voltage Largest Deviation Reliability Measure 08/17/11*



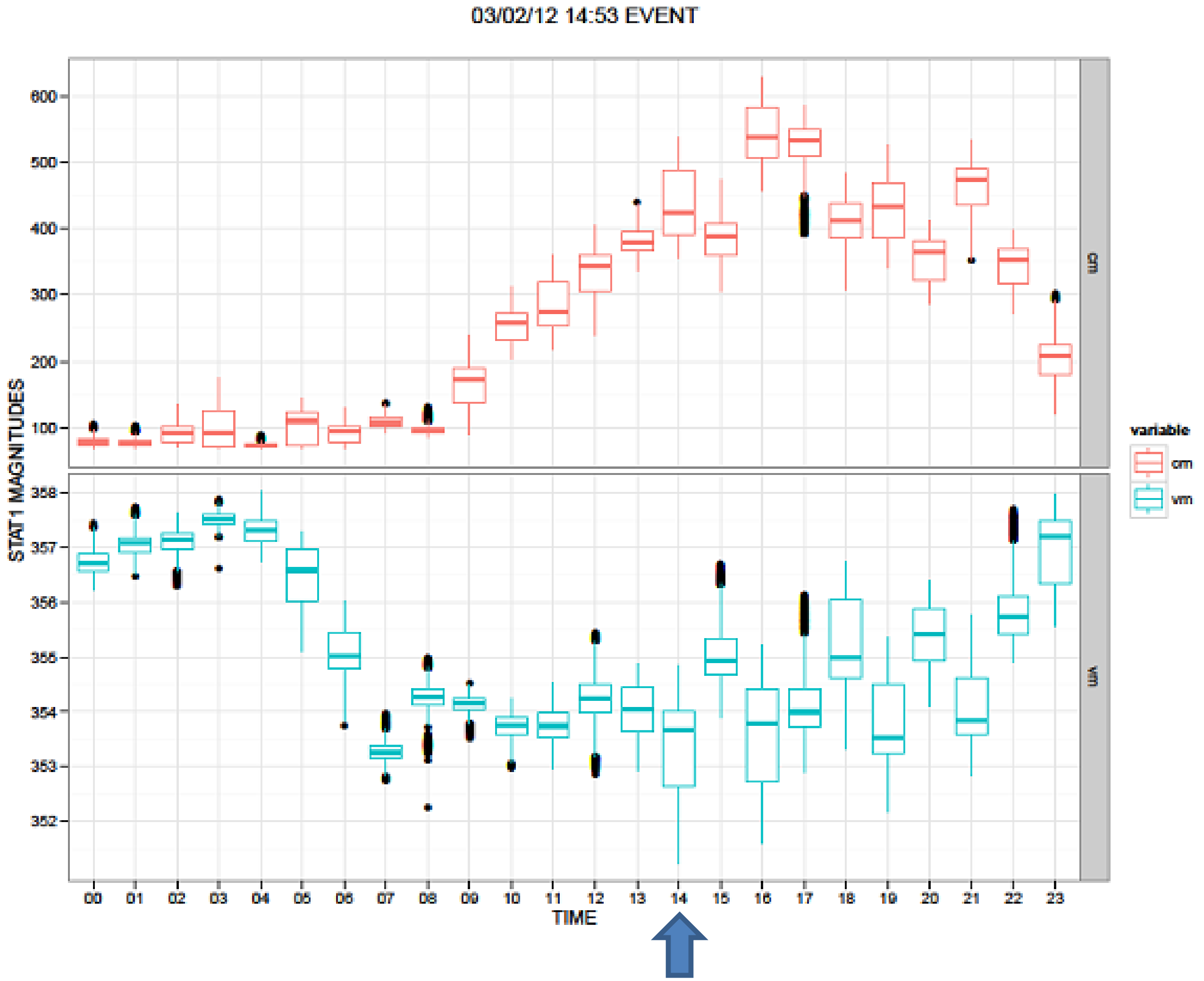
# *FREQUENCY AND VOLTAGE ALARMS IDENTIFICATION CRITERIA UNSING 03/02/12 DATA "DISTURBANCE DAY"*

# *Frequency Events Identification Criteria Event for Event on 03/02/12 at 14:53 in Eastern*

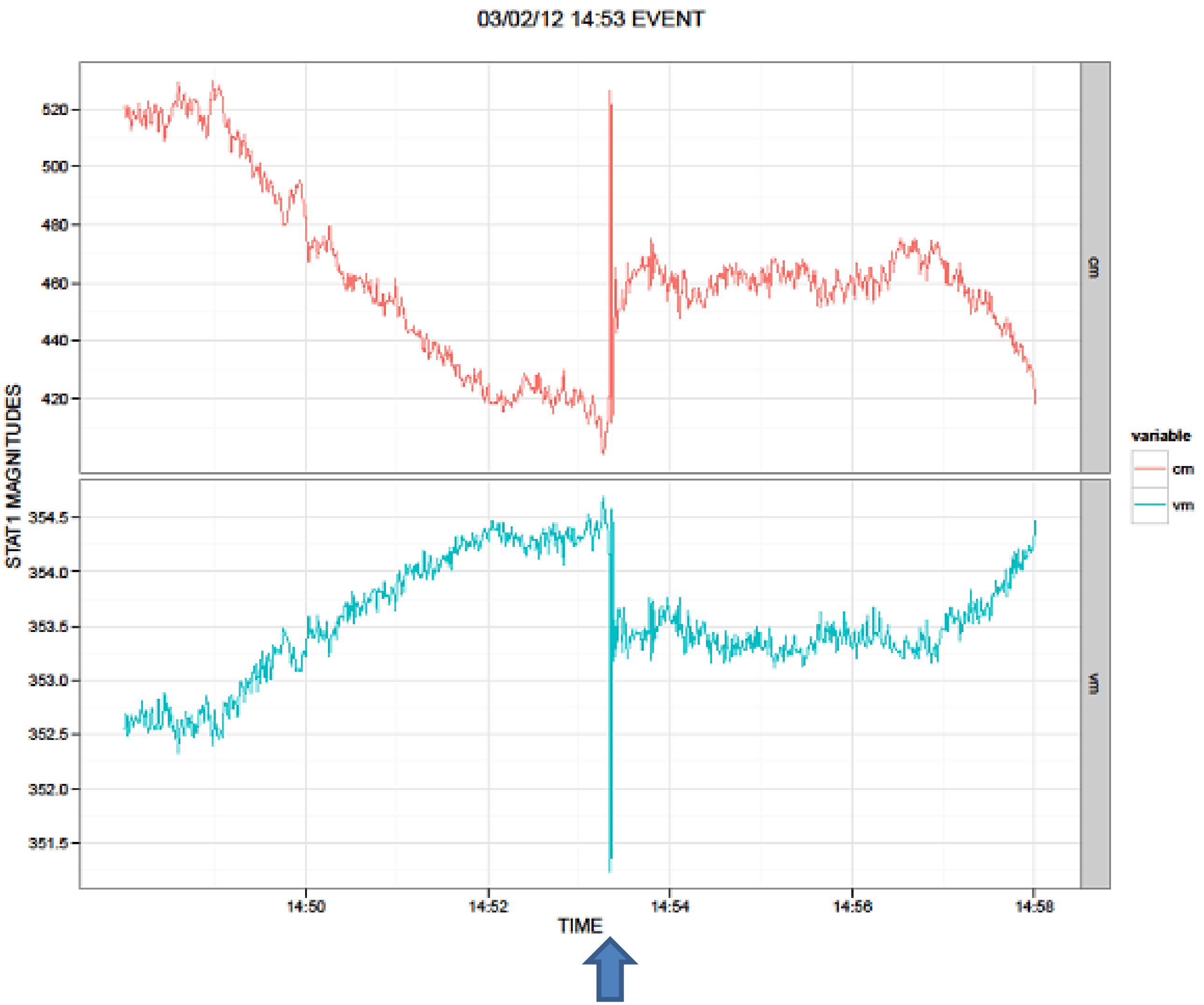
A frequency event is detected, captured and archived if during a 15-second rolling window the frequency jumps beyond a pre-defined threshold for each Interconnection



# STA1 Voltage–Current 24-Hour Profile Using Phasor 03/02/12 Data – Disturbance Day

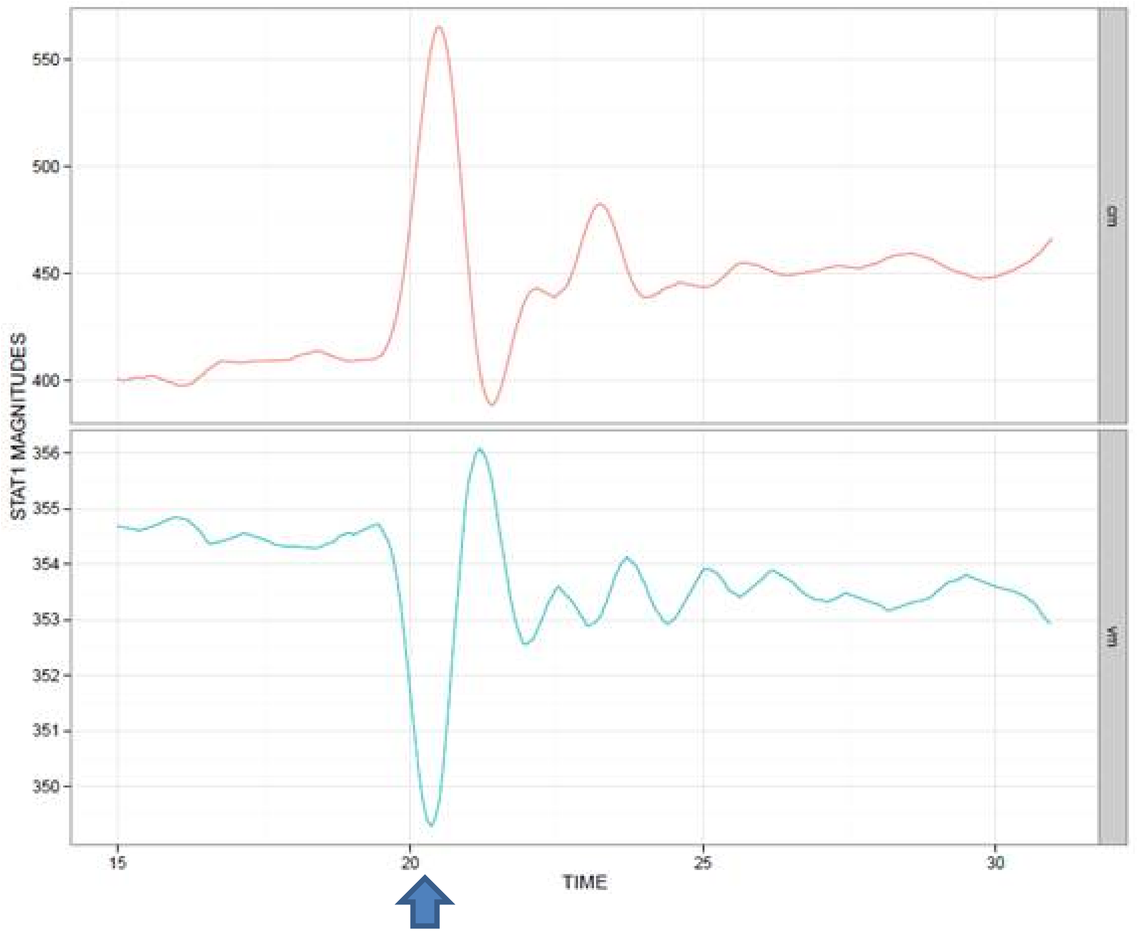


# *STA1 Voltage-Current 10-Minute Profile Using Phasor 03/02/12 Data*



# 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*

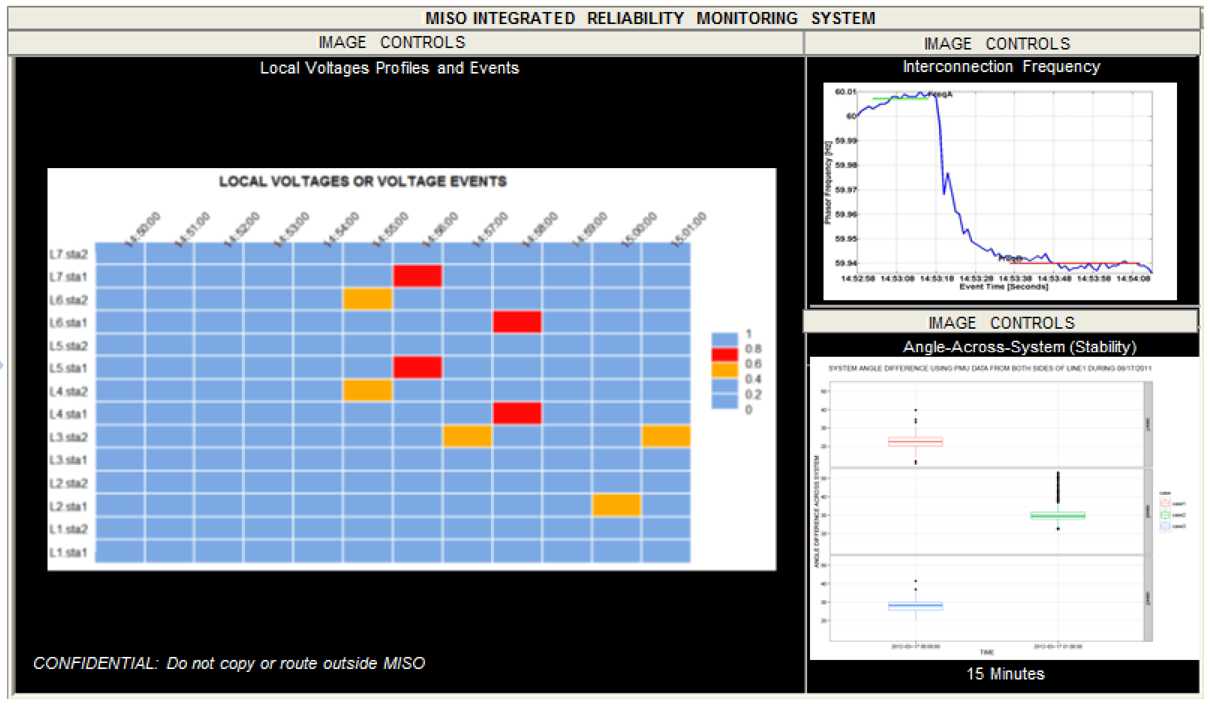
# Propose RPM Prototype Notifications and User Interface

**Objective** : Monitor frequency, voltage and stability in an ***integrated*** manner, using ***consistent*** notifications, ***simple*** graphical visualizations, ***model-less*** algorithms and ***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




SECURITY CONST. DISPATCH

**Notifications Via Alarms, Alerts and Reports**

**Interactive Reliability Monitoring Display**

# ***DAILY AND ON-DEMAND RELIABILITY REPORT***

# Daily Report Template – Pages 1-2



### 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

Event Frequency at points A, B, and C are shown in the frequency response table. The frequency for this event dropped 0.065Hz (point-A - point-C) and stabilized (point-B) in 21 seconds.

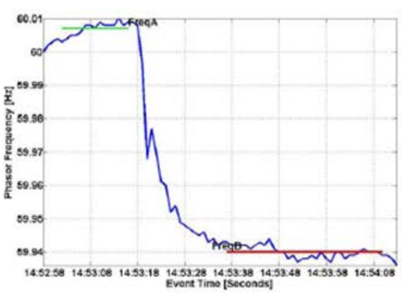



Fig 1 - 1-Second Frequency-Time Graph (Extend to 15 Minutes)

#### 2.2 Largest Frequency Event Data - Estimated Frequency Response

The event reached a lowest frequency of 59.942 (Point C) Hz and started returning to normal in about 21 seconds.

| DISCLAIMER- The event Frequency Response is an approximate estimate value using the best available 1-second phasor frequency data, ACE 1-minute SCADA data, and equations shown below whose definition is being developed by NERC Subcommittees and Frequency Response Standard Drafting team. Provided solely for informational purposes | |
|---|---|
| FR = MWLoss/10*DeltaFreq | MWLoss = Max(DeltaACE(BA))-Const*10*FreqBias*DeltaFreq |
| DeltaFreq = FreqA - FreqB | EI Const = 0.6, WI Const = 0.6, ERCOT = 0.3 |
| FreqA=Avg of t-2Sec to t-16Sec | |
| FreqA=Avg of t+19Sec to t+52Sec | |
| Event Summary: Date/Time | 3/2/2012 2:53:18 PM |
| Frequency at Point A [Hz] | 60.007 |
| Frequency at Point B [Hz] | 59.94 |
| Delta Frequency | -0.067 |
| BA with Highest Delta ACE | PJM |
| Highest Delta ACE [MW] | -1239 |
| FreqBias of the BA [MW/0.1Hz] | -1497 |
| MW Loss [MW] | 1841 |
| Estimated Event FreqResp [MW/0.1Hz] | -2747 |

The interconnection responded to the largest event with an estimated frequency response of about -2747 MW/0.1Hz over performing the yearly committed value of -2601 MW/0.1 Hz. (additional performance parameters will be included)

#### 2.3 Largest Voltage Event Data - 1 Second Voltage - Current Time Graph

Figure 2 shows the voltage and current profiles at a sub-second resolution during the 03/02/12 disturbance at 14:53 EST.

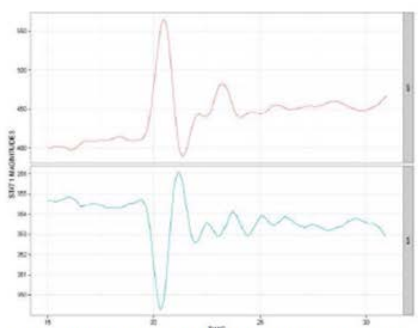


Fig 2 - Voltage and Current Profile at Disturbance on 03/02/12 at 14:53 EST





#### 2.3 Largest Voltage Event Data - Esimated Response

Table with significant voltage event parameters (WORK IN PROGRESS)

| Voltage Event Parameters | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

### 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 line with the most critical and risky margins during the last 24 hours.

| MISO Grid Performance Margins | | | | | |
|---|---|---|---|---|---|
| Hour | MISO Transmission Line | ANGLE MARGIN | VOLTAGE MARGIN | THERMAL MARGIN | Observations |
| 20 | STA1 - 2 | 0.309 | 0.718 | NA | |
| 21 | STA2 - 3 | 0.309 | 0.718 | NA | |
| 22 | STA3 - 4 | 0.309 | 0.718 | NA | |
| 22 | STA4 - 5 | 0.309 | 0.718 | NA | |
| 19 | STA5 - 6 | 0.309 | 0.718 | NA | |
| 23 | STA6 - 7 | 0.309 | 0.718 | NA | |

#### 3.1 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.

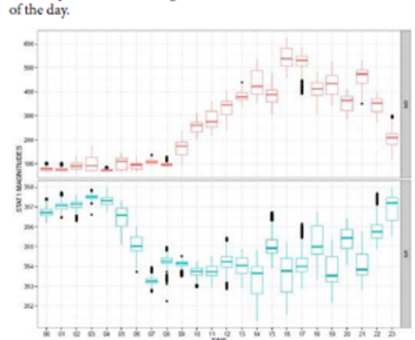


Fig 3 - Voltage and Current Distribution For Each Hour of the Day fot STA1

# *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*

| No. | Deployment Activity | Est. Comp. Date |
|---|---|---|
| 1 | CERTS - Presentation of Prototype preliminary validation results at MISO | 03/22/2012 |
| 2 | CERTS - Complete Prototype validations results using 03/02/12 phasor data | 04/13/2012 |
| 3 | MISO-Review Prototype Functional Spec. and give feedback to CERTS | 04/18/2012 |
| 4 | 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 | 05/26/2012 |
| 5 | MISO – CERTS Continue and complete Prototype Deployment | ??/??/2012 |
| 6 | CERTS – MISO Define and Create Prototype Field Trial plan | 06/15/2012 |
| 7 | CERTS-MISO – Execute Field Trial | 07/27.2012 |
| 8 | CERTS – MISO Final Report, Conclusions, Recommendations | 09/14/2012 |