Consortium for Electric Reliability Technology Solutions

Reliability Performance Monitoring Prototype

RELIABILITY PERFORMANCE MONITORING (RPM) USING PHASOR AND SCADA MEASUREMENTS

PROTOTYPE FUNCTIONAL SPECIFICATION FOR MISO

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MISO

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1 INTRODUCTION

The objectives of the Reliability Performance Monitoring (RPM) project are the research, functional specification, deployment, and field test of a prototype application producing Load-Generation control and Grid Reliability performance metrics using model-less algorithms running with MISO phasor data in MISO phasor infrastructure. The prototype leverages on CERTS, Advanced Systems Researchers (ASR), and University of Illinois experience researching and prototyping wide-area reliability monitoring applications and visualizations. The prototype performance metrics will be presented to MISO operations via alarms, real time performance monitoring displays and in automatically daily or on demand reliability performance reports.

Section 2 describes MISO the prototype host and the Bulk Power System (BPS) components with the corresponding phasor data being used for the prototype. Section 3 describes the RPM prototype research and development process. Section 4 describes MISO phasor data sources and its phasor data communications architecture. Section 5 presents the model-less algorithms to estimate Grid adequacy performance metrics. Section 6 presents preliminary results from the prototype algorithms, and section 7 describes preliminary validation results for the prototype three Grid performance metrics margins.

2 MISO - HOST OF RPM PROTOTYPE

The MISO manages one of the world's largest energy and operating reserves markets using security-constrained economic dispatch of generation. The Midwest Energy and Operating Reserves Market include a Day-Ahead Market, a Real-Time Market, and a Financial Transmission Rights (FTR) Market. These markets are operated and settled separately. The MISO was approved as the nation's first RTO in 2001 and is headquartered in Carmel, Indiana with an operations center in St. Paul, Minnesota.

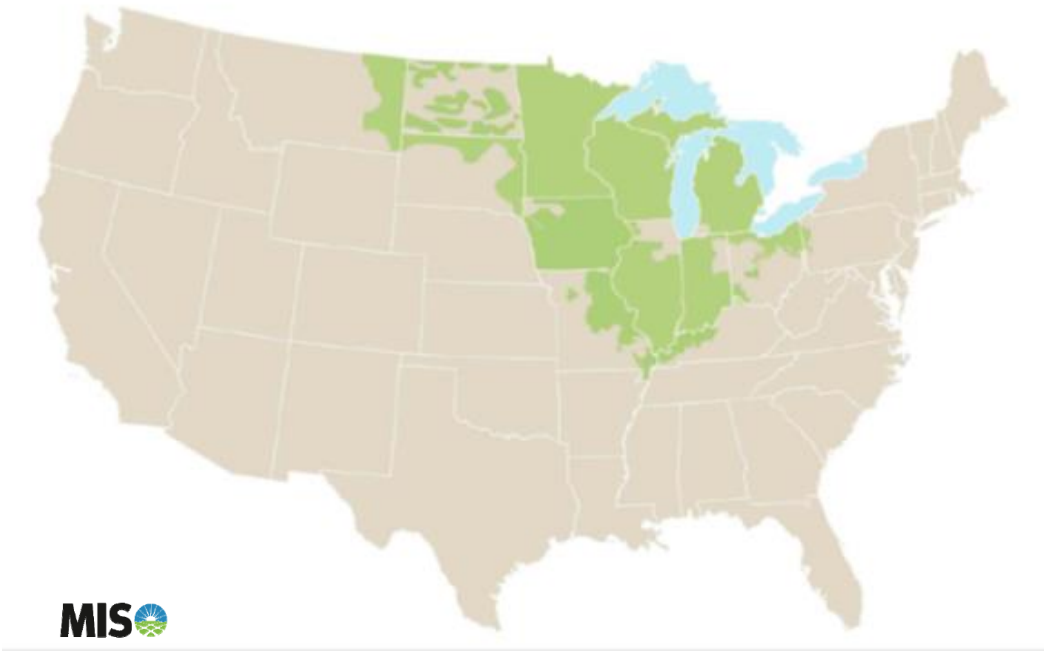


Figure 1 - MISO Territory – Host of Prototype

MISO's scale of committed operations:

- 114, 516 MW peak load (reliability, set August, 2010)
- 159,000 MW generation capacity (reliability region)
- 57,453 miles of transmission
- $17.4 billion in installed assets
- 35 transmission owners, including four stand-alone transmission owners
- 100 non-transmission owning members
- 750,000 square miles of service territory in all or parts of 13 states and 1 Canadian province

The CERTS prototype model-less algorithms require local phasor measurements at each side of transmission lines. Table 1 presents those MISO critical flowgates which currently have available phasor measurements at each side of each transmission line. It is expected the number of MISO critical flowgates will be 3 to 5 times within the next 2 to 3 years.

Table 1 – 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

Figure 2 shows the MISO 345KV level area whose phasor data is being used for the RPM prototype preliminary tests and validations.

Figure 2 - MISO Arpin-Rocky Run- Gardner Park with Phasor Measurements Available

3 RPM PROTOTYPE RESEARCH AND DEVELOPMENT PROCESS

3.1 CERTS Portfolio of Real-Time Monitoring Applications Including RPM Prototype

Figure 3 shows the portfolio of real time wide area monitoring applications researched and developed by CERTS for use by NERC reliability coordinators, reliability subcommittees and NERC, FERC, DOE Technical Staff. The RPM prototype is under research, development and field test.

The RPM prototype will leverage in some of the algorithms and visualizations from the CERTS portfolio of monitoring applications shown in Figure 3.

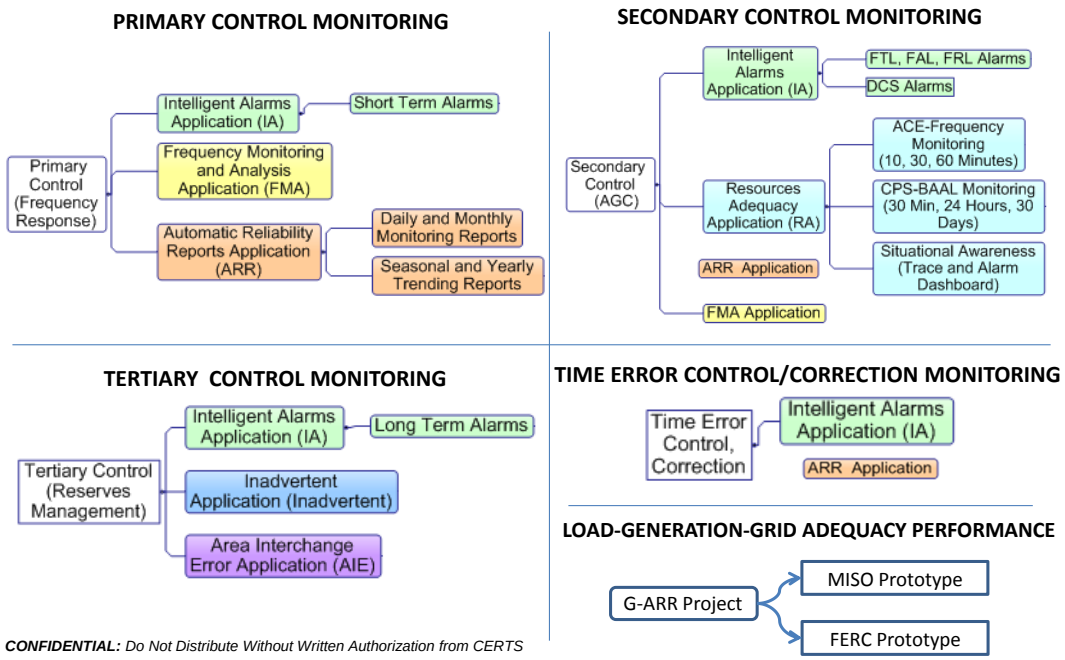


Figure 3 - MISO RPM Prototype – Part of CERTS Portfolio of Reliability Monitoring Applications

3.2 RPM Prototype Research Development Process

Figure 4 top half shows the load-generation control three performance metrics and the process to produce CERTS ARR reports currently in production. In parallel and equivalently Figure 4 bottom half shows the Grid performance metrics and process the RPM prototype require to present its monitoring displays and daily performance reports.

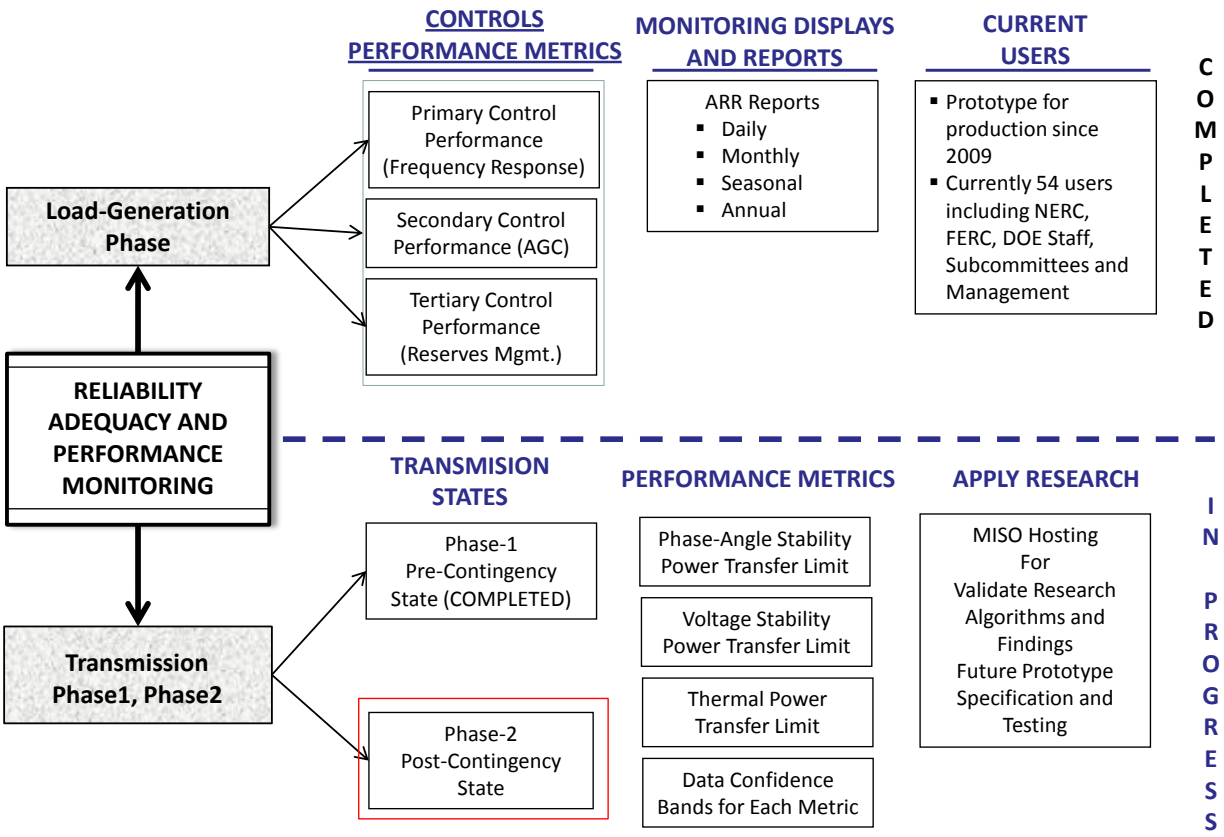


Figure 4 – Performance Metrics and Process to Produce RPM Reports

4 PHASOR DATA SOURCES AND DATA COMMUNICATIONS

The key building blocks for the RPM prototype are data access to historical archived data from the MISO phasor Data Sources, transfer of the data, and processing and analysis of the data for displays and for producing the daily report. Figure-5 shows MISO phasor architecture data flow.

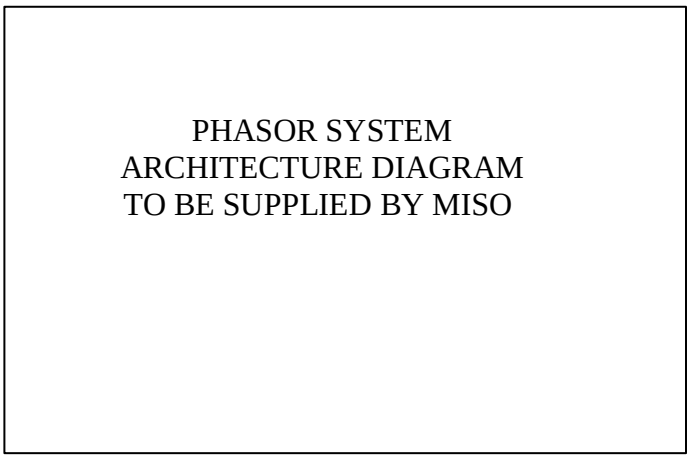


Figure 5 – Data Sources Architecture

5 PROTOTYPE MODEL-LESS ALGORITHMS GRID PERFORMANCE METRICS DESCRIPTION AND PHASOR DATA REQUIREMENTS

Following we describe how to calculate operational reliability metrics pertaining to voltage, thermal, and stability limits solely from phasor measurement on system lines. This work has been inspired by line loadability notions introduced by St. Clair[1], and further developed by Dunlop et al.[2] The computations carried out throughout the report are based on three assumptions i) all phasor measurements are positive sequence ii) phasor measurements have been filtered to compensate for errors in the sampling algorithms used in the phasor estimation process, and iii) data quality issues involving missing and repeated data have been addressed beforehand. Phasor measurements include line to line voltages in volts and 3-phase power in Watts and Vars.

Three Deterministic Transmission Adequacy Performance Metrics for Each Reliability Coordinator Area and for 230 KV, 500 KV and 745 KV Levels, and One Composite Transmission Adequacy Metric for Each Interconnection:

- Transmission Adequacy Metric constraint by power angle stability (TAM1) - Hourly weighted average of the difference between the power transfer limit due to power-angle stability constraints and actual flows to ensure system is not expose to instability and separations

- Transmission Adequacy Metric constraint by voltage stability (TAM2) – Hourly weighted average of the difference between the power transfer limit due to voltage stability constraints and actual voltages to maintain adequate voltage profiles to prevent equipment damage or voltage and system collapse

- Transmission Adequacy Metric constraint by thermal limits (TAM3) – Hourly weighted average of the difference between the power transfer limit due to thermal limits and actual flows to maintain currents within acceptable thresholds to prevent equipment thermal damage

- Composite Transmission Adequacy Metric (CTAM) – (research in progress)

5.1 Model-Less Algorithms and Angle Across System Estimation Process

For voltage limits, it is necessary to obtain a per-second estimate of the voltage magnitude on both ends of the line. For thermal limits, it is necessary to obtain a per-second estimate of the complex power magnitude flowing into both ends of the line. For Stability limits, it is necessary to obtain an estimate of the *angle-across-system*.

We assume that the set of measurements available includes the line voltages at both ends of the line and the currents flowing into both ends of the line. Variables are sampled *N* times per second. Accordingly,

[1] H. P. S. Clair, "Practical concepts in capability and performance of transmission lines," *Transactions of the American Institute of Electrical Engineers. Power Apparatus and Systems, Part III*, vol. 72, no. 2, pp. 1152 –1157, jan. 1953.

[2] R. Gutman, P. Marchenko, and R. Dunlop, "Analytical development of loadability characteristics for ehv and uhv transmission lines," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 2, pp. 606 –617, mar. 1979.

we denote by $\bar{V}_1[i,j] = V_1[i,j]\angle\theta_1[i,j]$ and $\bar{V}_2[i,j] = V_2[i,j]\angle\theta_2[i,j]$ be the phasor voltages measured on ends 1 and 2 of the line respectively, where *i* indexes time in seconds, and *j* = 1, 2 · · · , *N* indexes the samples taken every second *i*. Similarly, $\bar{I}_1[i,j] = I_1[i,j]\angle\gamma_1[i,j]$ and $\bar{I}_2[i,j] = I_2[i,j]\angle\gamma_2[i,j]$ denote the phasor currents measured following out of ends 1 and 2 of the line, where *i* indexes time in seconds, and *j* = 1, 2 · · ·, *N* indexes the samples taken every second *i*. We discuss next how to obtain the voltage magnitude, complex power magnitude, and angle-across-system estimates from these available phasor measurements.

5.1.1. Grid Performance Metrics Data Requirements

Let 1 and 2 be the extremes of the line being monitored. Assume we have measurements of voltages at both ends of the line and the currents flowing into both ends of the line. Assume we have N measurements per second. We need per second estimates of:

- Voltage magnitudes on both ends of the line, to monitor voltage limits;
- Complex power magnitudes, to monitor thermal limits;
- Angle across system, for stability limits;

Per second line-to-neutral voltages at second i are obtained as the average of phasor measurements, as follows (we assume Y connection):

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

To compensate for off-nominal frequency operation of the system and for simplification, we redefine voltage phase estimates as follows:

$$\hat{\theta}'_{1\phi}[i] = \frac{1}{N}\sum_{j=1}^{N} \theta'_{1\phi}[i,j] = \frac{1}{N}\left(\sum_{j=1}^{N} \theta_1[i,j] - \sum_{j=1}^{N} \theta_1[i,j]\right) = 0,$$
$$\hat{\theta}'_{2\phi}[i] = \frac{1}{N}\sum_{j=1}^{N} \theta'_{2\phi}[i,j] = \frac{1}{N}\left(\sum_{j=1}^{N} \theta_2[i,j] - \sum_{j=1}^{N} \theta_1[i,j]\right).$$

Per second Current estimates at second i are obtained in a similar way, assuming a Y connection for the system, as follows:

$$\hat{I}_{1\phi}[i] = \frac{\sum_{j=1}^{N} I_{1\phi}[i,j]}{N}, \gamma_{1\phi}[i] = \frac{\sum_{j=1}^{N} \gamma_1[i,j]}{N},$$
$$\hat{I}_{2\phi}[i] = \frac{\sum_{j=1}^{N} I_{2\phi}[i,j]}{N}, \gamma_{1\phi}[i] = \frac{\sum_{j=1}^{N} \gamma_2[i,j]}{N}.$$

where $I_{1\emptyset}[i,j] = I_1[i,j]$, and $I_{2\emptyset}[i,j] = I_2[i,j]$. As it was the case for voltages, to compensate for system operation at off-nominal frequency and for simplification, the current phase estimates are obtained as follows:

$$\hat{\gamma}'_{1\phi}[i] = \frac{1}{N}\sum_{j=1}^{N}\gamma'_{1\phi}[i,j] = \frac{1}{N}\left(\sum_{j=1}^{N}\gamma_1[i,j] - \sum_{j=1}^{N}\theta_1[i,j]\right),$$
$$\hat{\gamma}'_{2\phi}[i] = \frac{1}{N}\sum_{j=1}^{N}\gamma'_{2\phi}[i,j] = \frac{1}{N}\left(\sum_{j=1}^{N}\gamma_2[i,j] - \sum_{j=1}^{N}\theta_1[i,j]\right).$$

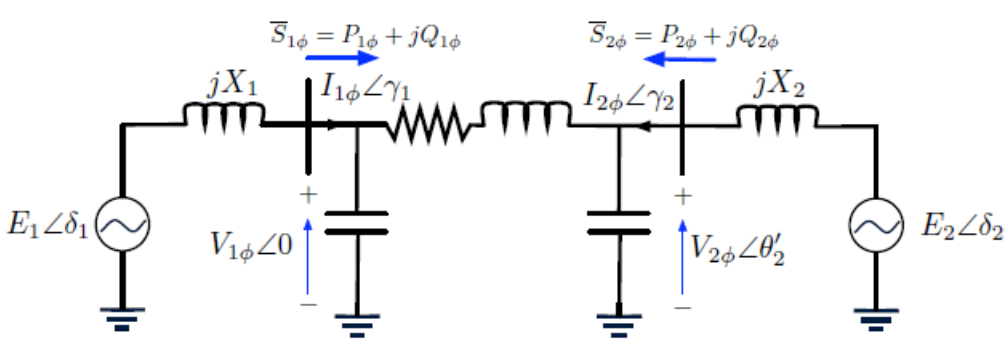
Per second estimates of Complex Powers at second i are obtained on the basis of estimates of voltages and currents as follows:

$$\hat{\bar{S}}_{1\phi}[i] = \frac{1}{N}\sum_{j=1}^{N}\left(V_{1\phi}[i,j]\angle\theta_{1\phi}[i,j] \cdot (I_{1\phi}[i,j]\angle\gamma_{1\phi}[i,j])^*\right)$$
$$\hat{\bar{S}}_{2\phi}[i] = \frac{1}{N}\sum_{j=1}^{N}\left(V_{2\phi}[i,j]\angle\theta_{2\phi}[i,j] \cdot (I_{2\phi}[i,j]\angle\gamma_{2\phi}[i,j])^*\right)$$

And three-phase complex power estimates at second ***i*** are obtained by:

$$\hat{\bar{S}}_{1}[i] = \frac{1}{N}\sum_{j=1}^{N}3\left(V_{1\phi}[i,j]\angle\theta_{1\phi}[i,j] \cdot (I_{1\phi}[i,j]\angle\gamma_{1\phi}[i,j])^*\right)$$
$$\hat{\bar{S}}_{2}[i] = \frac{1}{N}\sum_{j=1}^{N}3\left(V_{2\phi}[i,j]\angle\theta_{2\phi}[i,j] \cdot (I_{2\phi}[i,j]\angle\gamma_{2\phi}[i,j])^*\right)$$

Per second Angle-Across System are estimated by using for the monitored line a representation based on external Thevenin equivalents on both ends, as indicated in the figure below. We assume that the Thevenin impedance is purely imaginary and that the magnitude of the Thevenin voltage source is constant.



Let E_1 and E_2 denote the Thevenin voltages on ends 1 and 2 of the line respectively, and let δ_1 and δ_2 be the Thevenin voltage sources angles. Let jX_1 and jX_2 be the corresponding Thevenin impedances. Per-second estimates of X_1[i], and X_2[i] can be obtained on the basis of two consecutive one-second measurements, by solving the following quadratic equations and taking the positive roots.

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

Where

$$A_1[i] = \hat{I}_{1\phi}[i]^2 - \hat{I}_{1\phi}[i-1]^2,$$
$$B_1[i] = 2\hat{I}_{1\phi}[i]\hat{V}_{1\phi}[i]\sin(\hat{\theta}_{1\phi}[i] - \hat{\gamma}_{1\phi}[i]) - 2\hat{I}_{1\phi}[i-1]\hat{V}_{1\phi}[i-1]\sin(\hat{\theta}_{1\phi}[i-1] - \hat{\gamma}_{1\phi}[i-1]),$$
$$C_1[i] = \hat{V}_{1\phi}[i]^2 - \hat{V}_{1\phi}[i-1]^2,$$
$$A_2[i] = \hat{I}_{2\phi}[i]^2 - \hat{I}_{2\phi}[i-1]^2,$$
$$B_2[i] = 2\hat{I}_{2\phi}[i]\hat{V}_{2\phi}[i]\sin(\hat{\theta}_{2\phi}[i] - \hat{\gamma}_{2\phi}[i]) - 2\hat{I}_{2\phi}[i-1]\hat{V}_{2\phi}[i-1]\sin(\hat{\theta}_{2\phi}[i-1] - \hat{\gamma}_{2\phi}[i-1]),$$
$$C_2[i] = \hat{V}_{2\phi}[i]^2 - \hat{V}_{2\phi}[i-1]^2.$$

The estimates of $\hat{\bar{E}}_{1\emptyset}[i]$ and $\hat{\bar{E}}_{2\emptyset}[i]$ can be obtained as follows:

$$\bar{E}_{1\phi}[i] = \hat{E}_{1\phi}[i]\angle\hat{\delta}_{1\phi}[i] = \hat{V}_{1\phi}[i]\angle\hat{\theta}_{1\phi}[i] + \hat{I}_{1\phi}[i]\angle\hat{\gamma}_{1\phi}[i]\cdot j\hat{X}_1[i],$$
$$\bar{E}_{1\phi}[i] = \hat{E}_{2\phi}[i]\angle\hat{\delta}_{2\phi}[i] = \hat{V}_{2\phi}[i]\angle\hat{\theta}_{2\phi}[i] + \hat{I}_{2\phi}[i]\angle\hat{\gamma}_{2\phi}[i]\cdot j\hat{X}_2[i].$$

Then the estimate of angle-across-system δ_{12} can be obtained as follows:

$$\hat{\delta}_{12}[i] = \left\| \hat{\delta}_1[i] - \hat{\delta}_2[i] \right\|.$$

We now have all the elements needed to calculate grid reliability performance metrics margins, as follows:

5.2 Grid Reliability Performance Metrics Margins

5.2.1 Thermal Margins:

Per second thermal margin indexes on both ends of the line are calculated as:

$$L_1^{th}[i] = \frac{S_1^{max} - \hat{S}_1[i]}{S_1^{max}},$$
$$L_2^{th}[i] = \frac{S_2^{max} - \hat{S}_2[i]}{S_2^{max}}.$$

Alternative definitions for thermal margin reliability measures can be calculated on the basis of these indices as follows:

$$H_1^t = \max_i \{L_1^{th}[i]\},\ \ i = 1, 2, \cdots, 3600,$$

or:

$$AVG_1^t = \frac{1}{3600}\sum_{i=1}^{3600} L_1^{th}[i] = \frac{S_1^{max} - \frac{1}{3600}\sum_{i=1}^{3600}\hat{S}_1[i]}{S_1^{max}}.$$

The first reliability measured yields the normalized smallest line thermal margin for a one-hour period, while the second is an average margin, also for a one-hour period.

5.2.2 Voltage Margins

Per-second voltage margin indices can be obtained similarly as follows:

$$L_1^v[i] = \frac{(V_1^{nom} - \hat{V}_1[i])^2}{\Delta V_1^2},$$
$$L_2^v[i] = \frac{(V_2^{nom} - \hat{V}_2[i])^2}{\Delta V_2^2}.$$

On their basis, alternative voltage margin reliability measures are obtained as follows:

$$H_1^v = \max_i\{\sqrt{L_1^v[i]}\},\ i = 1, 2, \cdots, 3600,$$

That yields the normalized largest voltage deviation in a one-hour period, and

$$RMS_1^v = \sqrt{\frac{1}{3600}\sum_{i=1}^{3600} L_1^v[i]} = \frac{1}{\Delta V_1}\sqrt{\frac{1}{3600}\sum_{i=1}^{3600}(V_1^{nom} - \hat{V}_1[i])^2}.$$

Which yields an RMS reliability type measure.

5.2.3 Stability Margins

A per-second stability margin index can be defined as

$$L^s[i] = 1 - \sin(\hat{\delta}_{12}[i])$$

Similarly to the voltage and thermal reliability measures, alternative per-second stability margin reliability measures can be defined as follows:

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

That yields the normalized smallest angle-across-system margin for a one-hour period and

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

Which yields an average angle-across system margin, also for a one-hour period.

5.3 Stability Metric

The definition of L(s,i) is different in the Functional Specs, in the write-up and in the software:

5.3.1 Functional Specs

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

i = 1, 2 ,…, 3600 (seconds); the second term of the summation should have I as a subindex;

5.3.2 Write-up

$$L^s[i] = 1 - \sin(\hat{\delta}_{12}[i])$$

i=1,2, … , 3600 (seconds)

5.3.3 Software

The program only considers the first 40 seconds of each hour; it then calculates 300-rolling medians of all 1200 observations (1,199 to be precise), corresponding to 10 second intervals. Let's call these rolling medians: med(i); the program then defines:

L(s,i) = 1 – abs(sin(med(i))); i = 1, 2, … , 900 (300-observations rolling medians)

6 MODEL-LESS ALGORITHMS PRELIMINARY VALIDATION RESULTS

For the preliminary algorithms validation two sets of MISO phasor data were selected: the 24 hours of 08/17/11 as a normal operation day and the 24 hours of 03/02/12 as a significant disturbance day. Line-4 with terminal stations STA1 and STA2 was used for preliminary results validation.

6.2 Validation Results Using MISO August 17, 2011 (normal operation day) Phasor Data from Transmission Line-4

Using 8/17/12 data from MISO Line-4 the model-less algorithm estimates the per-second Angle-Across System. Randomly 3 minutes were selected to compare the estimate angle against the recommended threshold of 44 degrees. Figure 7 shows boxplots with the statistic parameters for each of the 3 minutes of angle-across-system (Case 1, 2, 3). Appendix-A shows the data and corresponding angle profile for each case. Further validations are taking place for getting angle statistics for each second of 8/17/11.

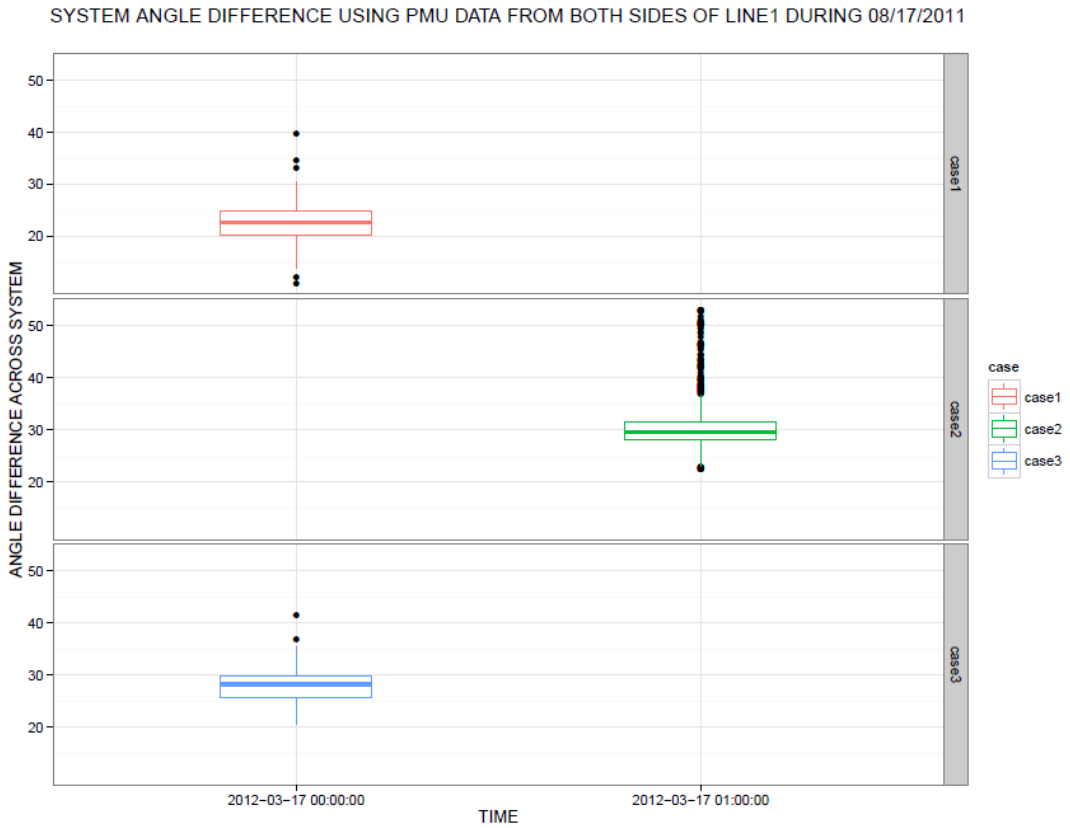


Figure 6 - System Angle Difference Using PMU Data for 8/17/11

(Waiting for U. Illinois data for all minutes of 8/17/11)

6.1 Validation Results Using MISO March 2, 2012 (disturbance day) Phasor Data from Transmission Line-4

Figure 8 shows the voltage and current profiles and statistics for each hour from 3/2/12, the disturbance day.

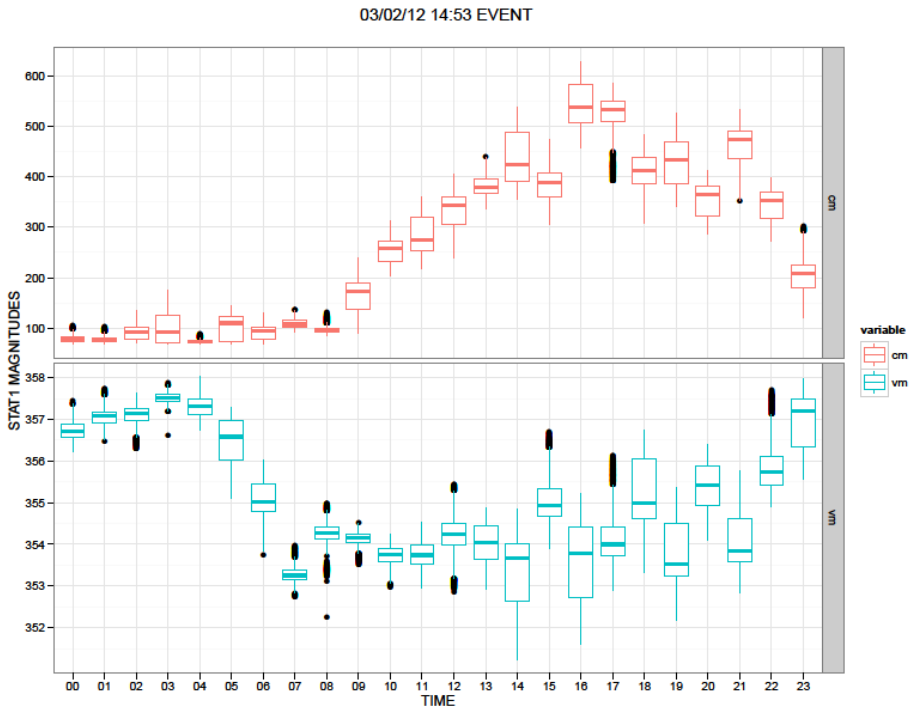


Figure 7 – STA1 Voltage-Current Profile Using PMU Data for 03/02/12

Figure 9 shows the voltage and current profiles 5 minutes before and after the tripping of 1841 MW of generation.

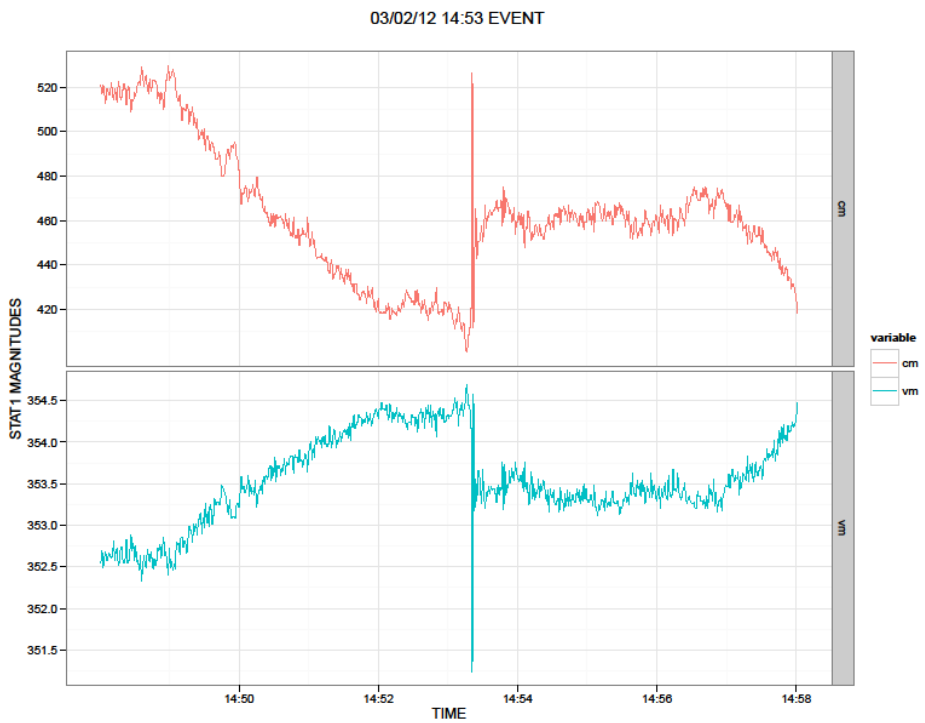


Figure 8 - STA1 Voltage-Current Profile Using PMU Data for 03/02/12

Figure 10 shows the voltage and current profiles at a sub-second resolution during the 03/02/12 disturbance at 14:53 EST.

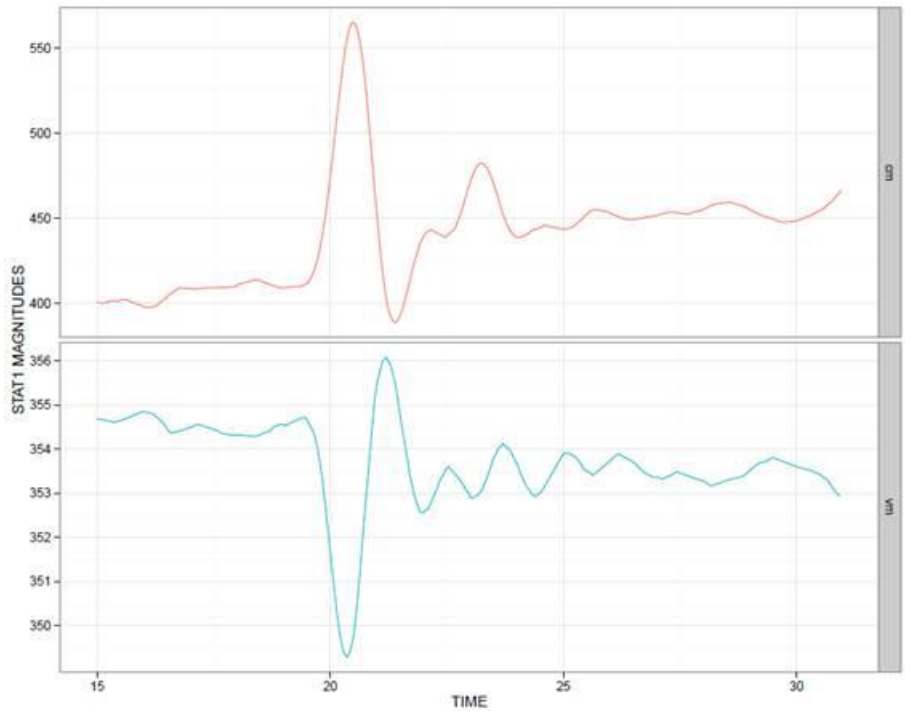


Figure 9 – STA1 Voltage-Current Profile at Disturbance on 03/02/12 at 14:53

WAITING FOR U. ILLINOIS RESULTS
FOR ALL MINUTES OF 3/2/12

Figure 10 – System Angle Difference Using PMU Data for 03/02/12

6.3 Angle Difference Across System Validation Using 10 MISO Other Transmission Lines

Final and more comprehensive validation of the prototype model-less algorithms and Grid Performance metrics will be done for the 10 critical MISO transmission lines for the five days of the largest frequency deviation in the Eastern Interconnection and the 2011 five largest Frequency Events in the interconnection.

7 GRID PERFORMANCE METRICS MARGINS VALIDATION RESULTS

For the preliminary validation, the three metrics were calculated per hour but the same calculation process can be applied per minute, 5-minutes, etc.

7.1 Stability Margin Reliability Measure

Figure 11 shows the normalized smallest angle-across system for each hour period for 8/17/11 produced with the following equation:

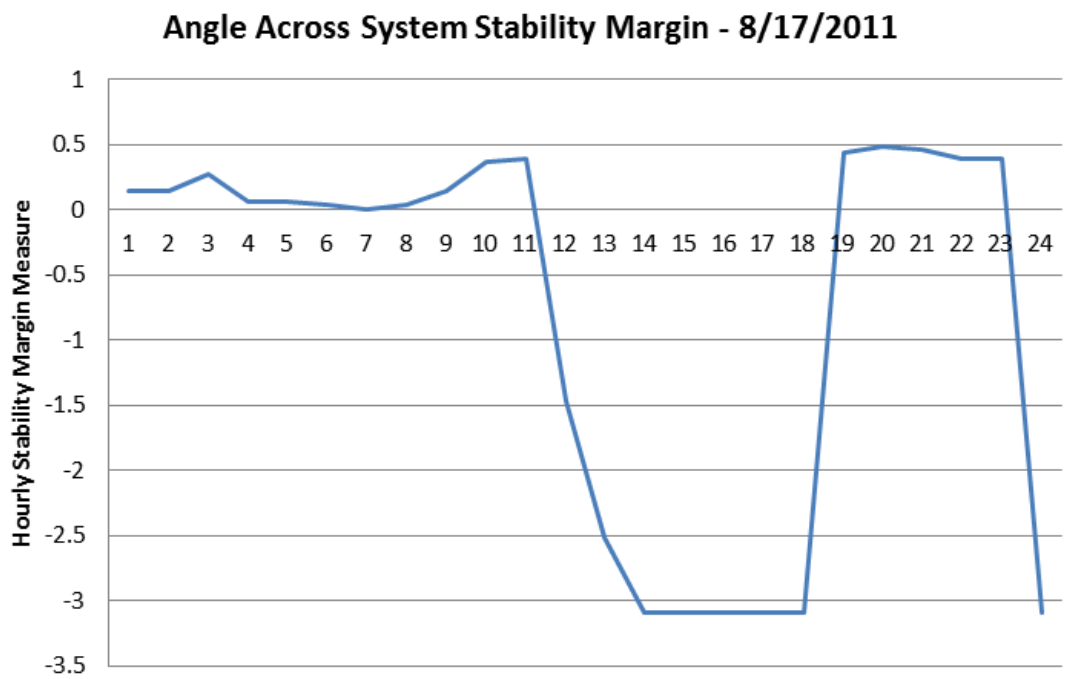


Figure 11 – Angle Across System Stability Margin – 8/17/2011

(UNIVERSITY OF ILLINOIS to describe metric and advantages/disadvantages for this Margin)

Figure 12 shows the average angle-across system margin for each hour period for 8/17/11 produced with the following equation:

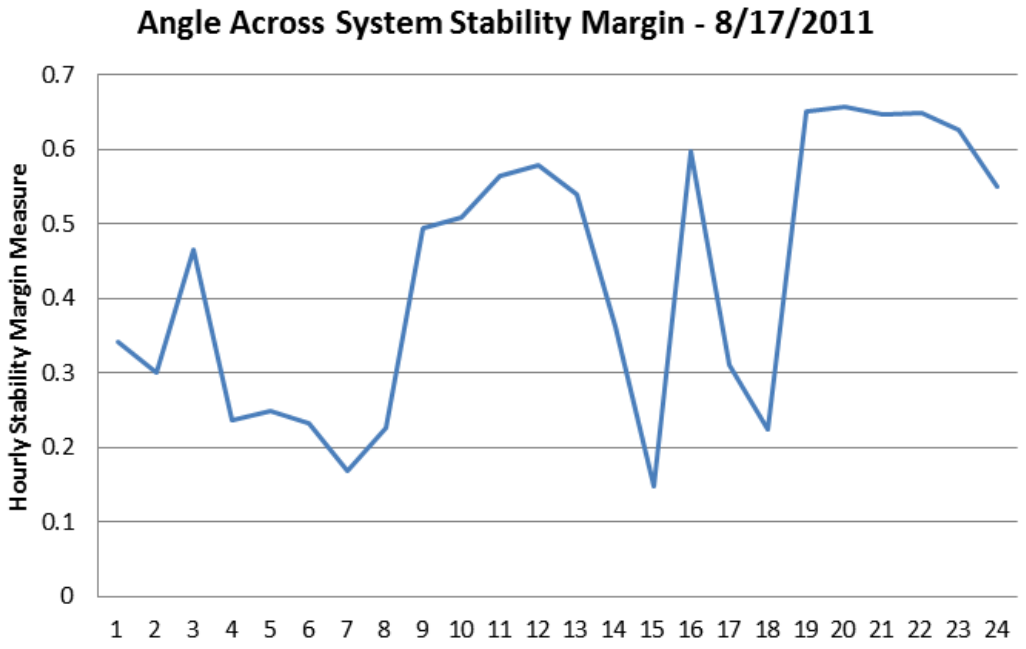


Figure 12 - Angle Across System Stability Margin – 8/17/2011

(UNIVERSITY OF ILLINOIS to describe metric and advantages/disadvantages for this Margin)

7.2 Voltage Largest Deviation – Hourly

Figure 13 shows the normalized voltage largest deviation for each hour period for 8/17/11 produced with the following equation:

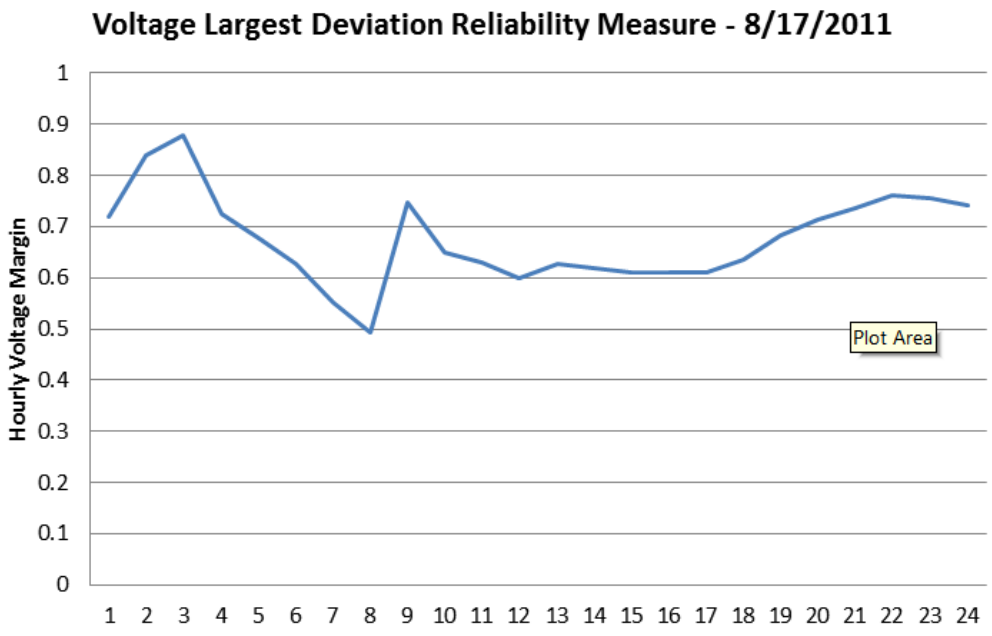


Figure 13 – Voltage Largest Deviation Reliability Measure – 8/17/2011

(UNIVERSITY OF ILLINOIS to describe metric and advantages/disadvantages for this Margin)
Figure 14 shows the normalized root-mean square voltage deviation for each hour period for 8/17/11.

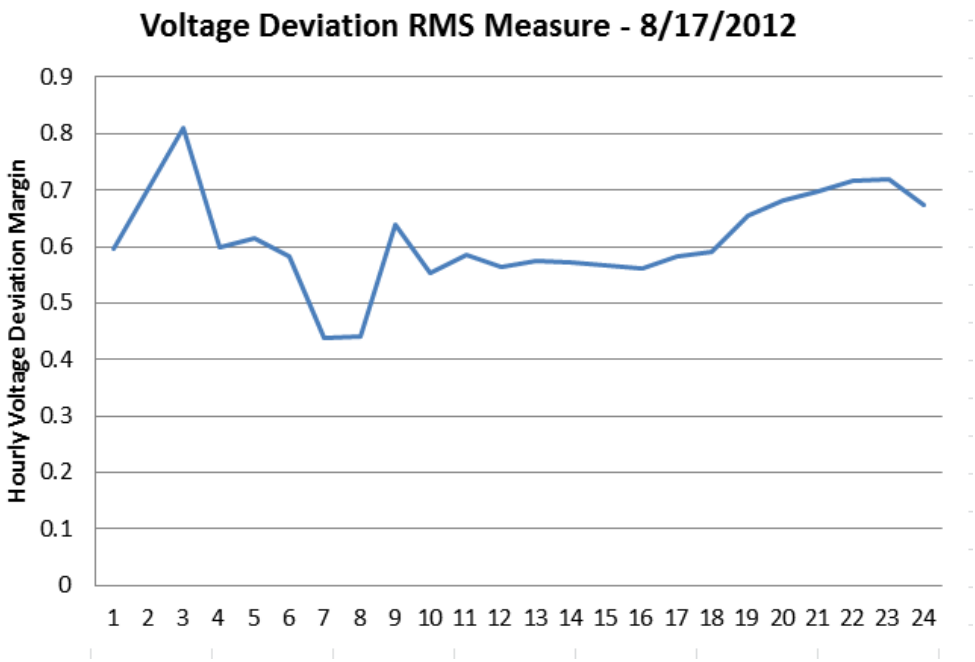


Figure 14 – Voltage Deviation RMS Measure – 8/17/2011

(UNIVERSITY OF ILLINOIS to describe metric and advantages/disadvantages for this Margin)

7.3 Thermal Margin

Figure 15 shows the normalized smallest line loadibility margin and the average line loadability margin.

WAITING FOR U. ILLINOIS RESULTS

Figure 15 – Thermal Margin

7.4 Results for Reliability Metrics for Voltages, Thermal And Stability Margins

7.4.1 5- Minute Period Hour 6 (7 a.m.)

Table 2 - Results for 5-Minute Period – Hour 6

5-Min Period	Hv1	RMSv1	Hv2	RMSv2	Ht1	RMSt1	Ht2	RMSt2	Hs	AVGs
1	0.60344	0.59198	0.54825	0.53708	0.99504	0.99493	0.97774	0.97607	0.99242	0.51458
2	0.59509	0.57876	0.54052	0.52504	0.99502	0.99472	0.97999	0.97823	0.99735	0.85152
3	0.57422	0.56297	0.52104	0.51091	0.99495	0.99455	0.98137	0.97879	0.99943	0.83630
4	0.62748	0.55522	0.54786	0.50155	0.99504	0.99421	0.98175	0.97922	0.99860	0.86922
5	0.63606	0.62484	0.55443	0.54309	0.99315	0.99279	0.97797	0.97595	0.99634	0.81079
6	0.63930	0.62367	0.56000	0.54440	0.99323	0.99301	0.97702	0.97515	0.99791	0.76779
7	0.62848	0.61197	0.55142	0.53714	0.99353	0.99330	0.97620	0.97362	0.99581	0.51245
8	0.61101	0.59396	0.53944	0.52172	0.99353	0.99340	0.97712	0.97383	0.99561	0.49482
9	0.59455	0.57759	0.52205	0.50283	0.99343	0.99297	0.97270	0.97011	0.90869	0.31447
10	0.58899	0.57541	0.51185	0.49792	0.99308	0.99279	0.97272	0.97022	0.97402	0.31089
11	0.58481	0.57228	0.50597	0.49457	0.99302	0.99248	0.97066	0.96830	0.81584	0.32693
12	0.56247	0.52911	0.48657	0.45790	0.99259	0.99176	0.96871	0.96591	1.00000	0.36650

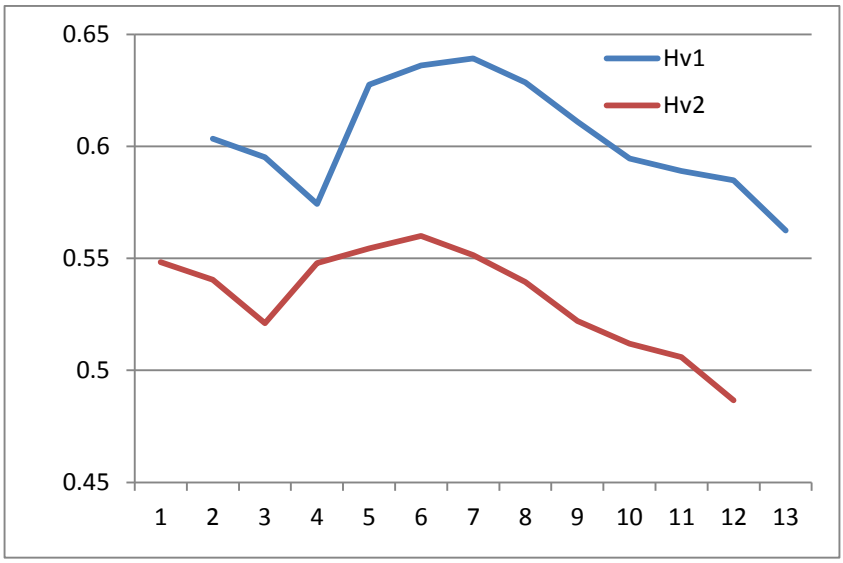


Figure 16 –

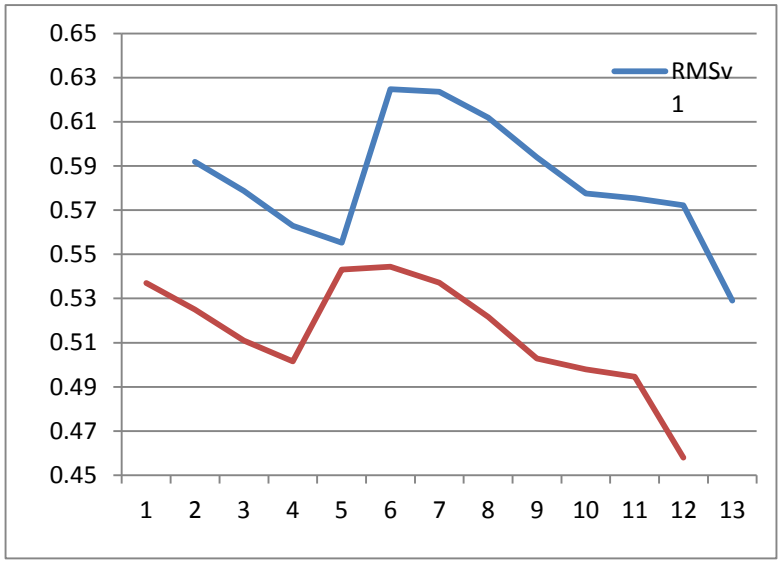


Figure 17 -

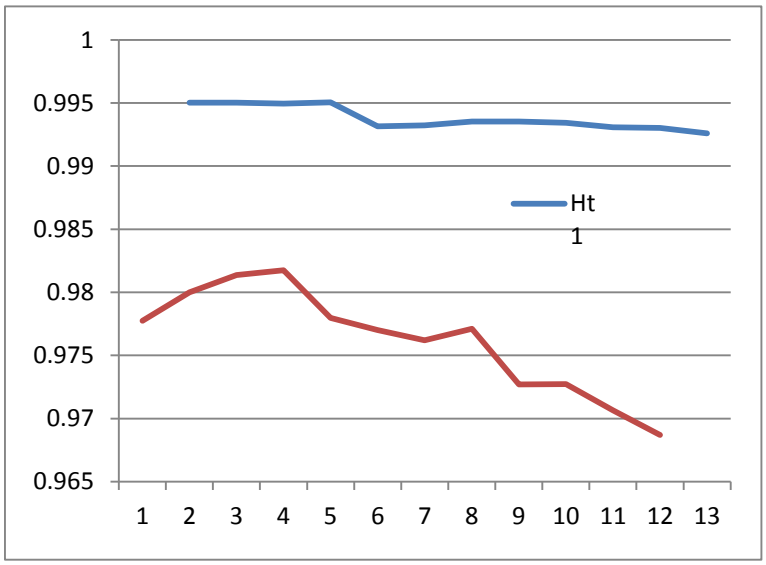


Figure 18 -

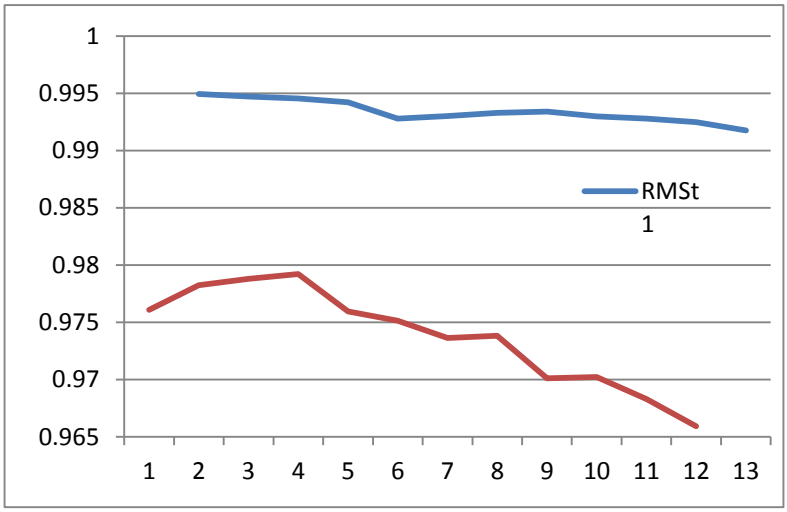


Figure 19 -

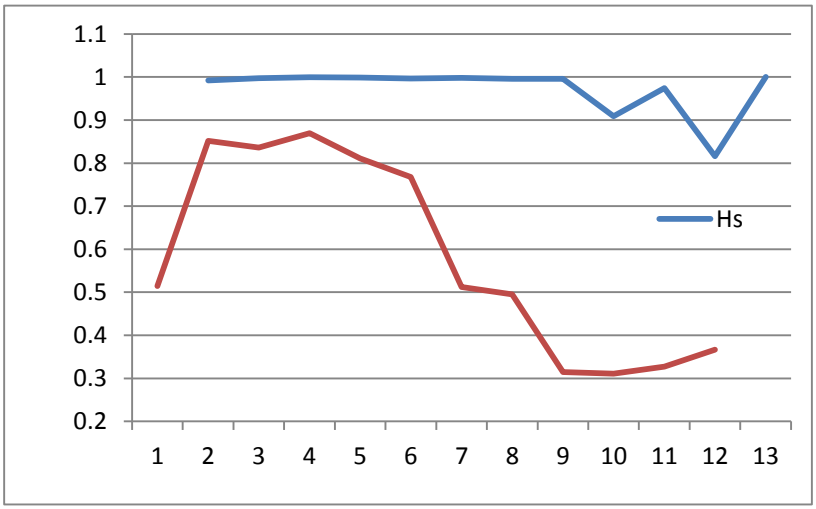


Figure 20 -

7.4.2 5- Minute Period Hour 21 (10 p.m.)

Table 3 –Results for 5-Minute Period – Hour 21

5-Min Period	Hv1	RMSv1	Hv2	RMSv2	Ht1	RMSt1	Ht2	RMSt2	Hs	AVGs
1	0.61797	0.58672	0.58226	0.55720	0.97285	0.97087	0.97366	0.97008	0.51431	0.27323
2	0.59293	0.57277	0.56309	0.54521	0.97131	0.96975	0.97089	0.96813	0.86413	0.27243
3	0.58481	0.54408	0.55606	0.52383	0.97035	0.96708	0.96923	0.96340	0.60540	0.25566
4	0.53527	0.50715	0.50968	0.48676	0.96737	0.96595	0.96347	0.96106	0.50599	0.25241
5	0.52839	0.50239	0.50419	0.48160	0.96701	0.96570	0.96292	0.96069	0.62082	0.25553
6	0.52352	0.50115	0.50064	0.48183	0.96668	0.96490	0.96224	0.95916	0.62532	0.25242
7	0.51316	0.48191	0.49546	0.46759	0.96467	0.96339	0.95881	0.95658	0.48524	0.23640
8	0.51772	0.48149	0.49299	0.46514	0.96595	0.96382	0.96110	0.95742	0.49581	0.24406
9	0.51911	0.49802	0.49407	0.47674	0.96674	0.96521	0.96241	0.95980	0.40765	0.24764
10	0.55814	0.52198	0.52282	0.49368	0.96935	0.96720	0.96664	0.96316	0.57178	0.25663
11	0.56603	0.54726	0.53047	0.51380	0.97095	0.96855	0.96936	0.96531	0.58665	0.27564
12	0.62454	0.57603	0.57530	0.53872	0.97485	0.97015	0.97511	0.96782	1.00000	0.27997

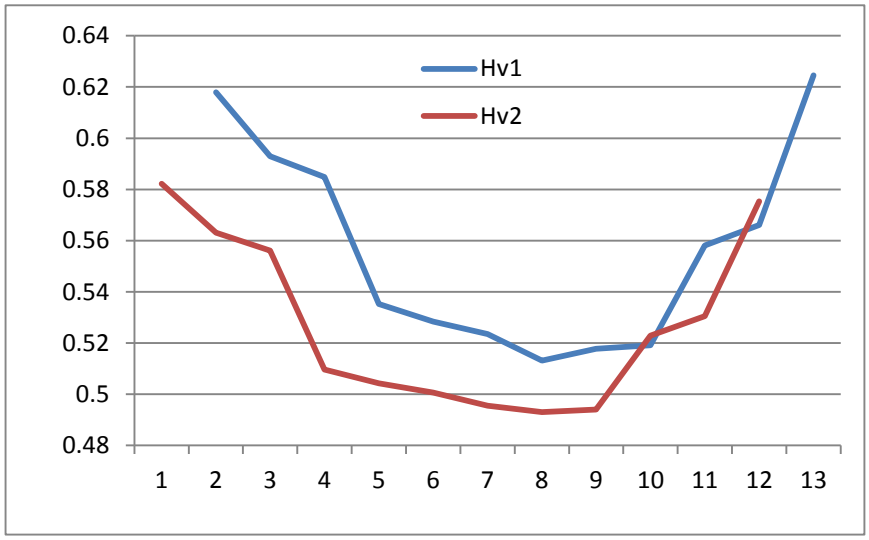


Figure 21 –

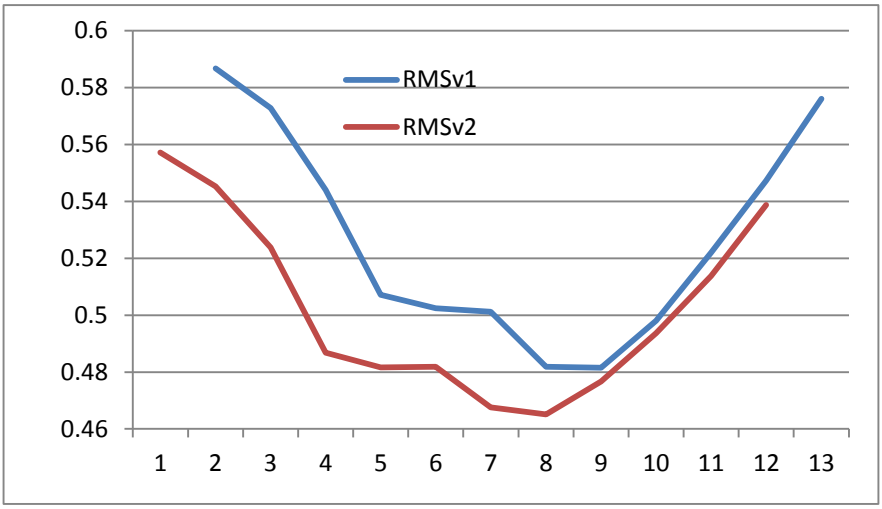


Figure 22 –

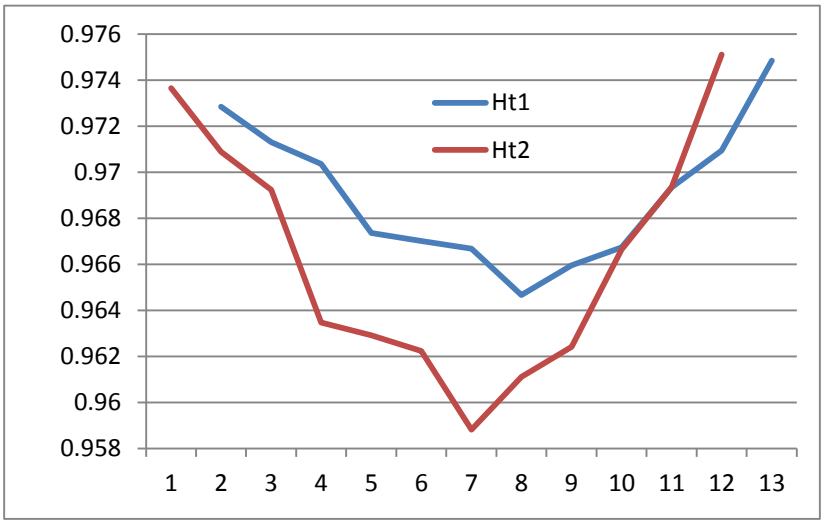


Figure 23 –

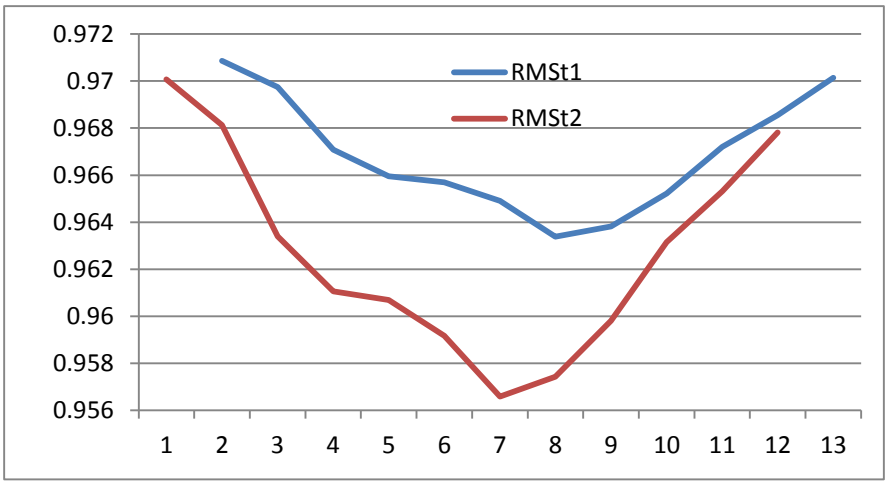


Figure 24 –

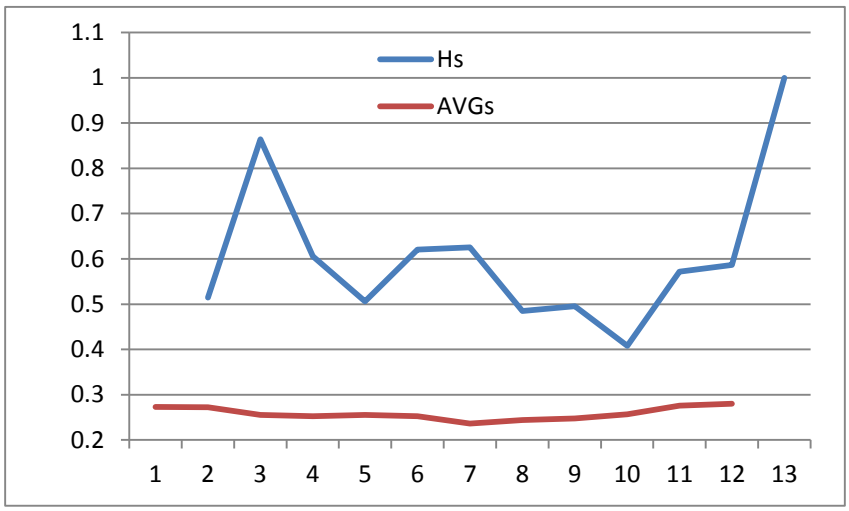


Figure 25 –

8 TRANSIENT STABILITY RESULTS

8.1 Hours 6 AM, 7 AM, 10 PM, 11 PM

Table 4 – Results for Hours 6 AM, 7 AM, 10 PM, 11 PM

Hour	freq	H	Hour	freq	H	Hour	freq	H	Hour	freq	H
6:00:40	0.5341	0.5497	**7:00:40**	0.3317	1.5868	**22:00:40**	0.4110	11.4947	**23:00:40**	0.4817	8.7966
6:01:20	0.3549	1.3120	**7:01:20**	0.5683	0.8025	**22:01:20**	0.3805	14.1299	**23:01:20**	0.3329	15.9280
6:02:00	0.2244	0.7098	**7:02:00**	0.4793	0.2196	**22:02:00**	0.4659	5.3884	**23:02:00**	0.4915	4.6840
6:02:40	0.3537	0.1996	**7:02:40**	0.4073	0.3671	**22:02:40**	0.4341	11.6477	**23:02:40**	0.4780	3.8678
6:03:20	0.4756	0.0211	**7:03:20**	0.3390	2.1363	**22:03:20**	0.5000	6.6537	**23:03:20**	0.3146	7.1605
6:04:00	0.6037	0.0577	**7:04:00**	0.1902	25.3623	**22:04:00**	0.1927	46.4611	**23:04:00**	0.4732	8.4519
6:04:40	0.5378	0.0026	**7:04:40**	0.2293	0.5913	**22:04:40**	0.4744	7.4943	**23:04:40**	0.4305	6.3557
6:05:20	0.5707	0.0436	**7:05:20**	0.4671	2.8175	**22:05:20**	0.4915	8.2068	**23:05:20**	0.4439	3.8501
6:06:00	0.7293	0.3515	**7:06:00**	0.5061	3.3491	**22:06:00**	0.4976	7.3395	**23:06:00**	0.2890	10.3528
6:06:40	0.6512	0.6691	**7:06:40**	0.4085	2.5050	**22:06:40**	0.2744	19.1784	**23:06:40**	0.3793	5.8065
6:07:20	0.5939	1.2375	**7:07:20**	0.3976	4.2604	**22:07:20**	0.2878	14.5074	**23:07:20**	0.4049	5.7969
6:08:00	0.5915	0.9842	**7:08:00**	0.4500	2.1857	**22:08:00**	0.5000	6.4292	**23:08:00**	0.4341	4.9874
6:08:40	0.5829	0.4282	**7:08:40**	0.2512	9.2646	**22:08:40**	0.3683	10.7801	**23:08:40**	0.4805	5.5617
6:09:20	0.5549	1.9406	**7:09:20**	0.3902	3.9798	**22:09:20**	0.3683	13.3725	**23:09:20**	0.5220	3.4998
6:10:00	0.5000	0.9082	**7:10:00**	0.5000	2.8664	**22:10:00**	0.5000	5.5147	**23:10:00**	0.4683	4.4423
6:10:40	0.4927	2.8552	**7:10:40**	0.2695	0.5929	**22:10:40**	0.4073	8.4632	**23:10:40**	0.4610	5.5020
6:11:20	0.5305	1.0779	**7:11:20**	0.4439	0.4755	**22:11:20**	0.5000	7.7090	**23:11:20**	0.4280	5.3685
6:12:00	0.5146	1.8357	**7:12:00**	0.2878	9.0717	**22:12:00**	0.4915	6.0420	**23:12:00**	0.4695	4.1129
6:12:40	0.6280	1.2963	**7:12:40**	0.4793	0.4927	**22:12:40**	0.5341	4.9033	**23:12:40**	0.5183	3.1849
6:13:20	0.5134	2.5991	**7:13:20**	0.2976	3.4532	**22:13:20**	0.3561	14.0171	**23:13:20**	0.5085	2.8617
6:14:00	0.2927	14.2287	**7:14:00**	0.3963	0.2241	**22:14:00**	0.5134	4.5442	**23:14:00**	0.4988	5.1333
6:14:40	0.3366	10.0588	**7:14:40**	0.3463	1.3143	**22:14:40**	0.5000	6.2986	**23:14:40**	0.4488	4.5141
6:15:20	0.1817	28.2157	**7:15:20**	0.4451	0.7464	**22:15:20**	0.4988	7.9659	**23:15:20**	0.4305	7.6475
6:16:00	0.2805	1.1603	**7:16:00**	0.3951	0.2887	**22:16:00**	0.3317	15.0455	**23:16:00**	0.4317	5.3850
6:16:40	0.3683	4.4553	**7:16:40**	0.4793	1.2574	**22:16:40**	0.4866	6.1632	**23:16:40**	0.5000	4.5332
6:17:20	0.5732	1.8236	**7:17:20**	0.5378	0.8352	**22:17:20**	0.3915	12.9763	**23:17:20**	0.4939	4.0757
6:18:00	0.5183	0.3441	**7:18:00**	0.4585	1.0193	**22:18:00**	0.4378	10.1851	**23:18:00**	0.3220	11.5315
6:18:40	0.5341	2.8653	**7:18:40**	0.3585	2.0528	**22:18:40**	0.4378	7.9297	**23:18:40**	0.4476	6.2434
6:19:20	0.2280	14.2109	**7:19:20**	0.6085	0.6178	**22:19:20**	0.4122	12.1586	**23:19:20**	0.5232	1.4816
6:20:00	0.5622	0.7759	**7:20:00**	0.4756	0.8167	**22:20:00**	0.4780	8.7020	**23:20:00**	0.4951	1.6705
6:20:40	0.4720	1.4148	**7:20:40**	0.4500	0.7831	**22:20:40**	0.4000	16.2194	**23:20:40**	0.3122	4.1131
6:21:20	0.5293	3.1195	**7:21:20**	0.1317	8.6589	**22:21:20**	0.3354	19.1566	**23:21:20**	0.4305	0.8170
6:22:00	0.5768	2.0402	**7:22:00**	0.5171	0.5151	**22:22:00**	0.4268	13.2008	**23:22:00**	0.4817	7.1125
6:22:40	0.4476	0.8506	**7:22:40**	0.4976	0.4204	**22:22:40**	0.4951	9.5590	**23:22:40**	0.4134	5.2979
6:23:20	0.5537	1.1541	**7:23:20**	0.5341	0.2491	**22:23:20**	0.3902	17.6134	**23:23:20**	0.4110	9.6855
6:24:00	0.3671	1.2200	**7:24:00**	0.2512	0.1533	**22:24:00**	0.3573	16.7562	**23:24:00**	0.3427	13.3463
6:24:40	0.5610	0.0738	**7:24:40**	0.4841	0.5399	**22:24:40**	0.4122	13.8774	**23:24:40**	0.4037	8.6275
6:25:20	0.4610	1.6263	**7:25:20**	0.4549	0.3783	**22:25:20**	0.4890	9.6215	**23:25:20**	0.4817	3.4069
6:26:00	0.3878	0.1818	**7:26:00**	0.4805	0.4875	**22:26:00**	0.5000	8.5037	**23:26:00**	0.4817	5.5125
6:26:40	0.5122	0.2466	**7:26:40**	0.4829	0.1433	**22:26:40**	0.5000	9.4007	**23:26:40**	0.4000	2.3295
6:27:20	0.2122	6.3400	**7:27:20**	0.3049	0.7360	**22:27:20**	0.5000	9.2822	**23:27:20**	0.5171	0.2484
6:28:00	0.3439	1.6702	**7:28:00**	0.2963	1.0862	**22:28:00**	0.3902	15.1214	**23:28:00**	0.4512	0.3442
6:28:40	0.4329	0.4146	**7:28:40**	0.4171	0.4534	**22:28:40**	0.4768	11.4338	**23:28:40**	0.4951	0.3192
6:29:20	0.2256	1.3578	**7:29:20**	0.4537	0.4213	**22:29:20**	0.4829	9.7283	**23:29:20**	0.4927	3.7375
6:30:00	0.4000	1.2132	**7:30:00**	0.3744	0.7371	**22:30:00**	0.4378	12.7094	**23:30:00**	0.4049	4.0765
6:30:40	0.2878	0.0153	**7:30:40**	0.3671	0.6499	**22:30:40**	0.4585	11.2599	**23:30:40**	0.4537	2.9500
6:31:20	0.3463	0.2845	**7:31:20**	0.3951	0.4910	**22:31:20**	0.2939	26.9700	**23:31:20**	0.4280	5.4341
6:32:00	0.4890	0.1207	**7:32:00**	0.4610	0.4500	**22:32:00**	0.4366	11.5840	**23:32:00**	0.3744	7.0332
6:32:40	0.2268	3.4937	**7:32:40**	0.2659	1.5651	**22:32:40**	0.4854	9.2024	**23:32:40**	0.4427	4.6130
6:33:20	0.4207	1.1997	**7:33:20**	0.4720	0.3170	**22:33:20**	0.4927	8.3411	**23:33:20**	0.2976	8.1837
6:34:00	0.4207	1.2048	**7:34:00**	0.4585	0.2024	**22:34:00**	0.4963	9.8685	**23:34:00**	0.3098	13.7729
6:34:40	0.4122	1.1097	**7:34:40**	0.4549	0.3227	**22:34:40**	0.4000	15.2185	**23:34:40**	0.4646	0.4504
6:35:20	0.3671	0.2480	**7:35:20**	0.5512	0.2027	**22:35:20**	0.4085	13.9151	**23:35:20**	0.4451	0.7439
6:36:00	0.4829	0.4368	**7:36:00**	0.4841	0.2081	**22:36:00**	0.4341	9.6164	**23:36:00**	0.4037	6.3240
6:36:40	0.3927	1.2788	**7:36:40**	0.4537	0.4483	**22:36:40**	0.5000	9.7134	**23:36:40**	0.3232	8.8102
6:37:20	0.3951	0.5348	**7:37:20**	0.3341	0.6760	**22:37:20**	0.5000	8.3362	**23:37:20**	0.3488	7.5837
6:38:00	0.2415	2.9153	**7:38:00**	0.3854	0.3527	**22:38:00**	0.5000	7.1930	**23:38:00**	0.3098	8.9660
6:38:40	0.1573	0.8059	**7:38:40**	0.3012	0.5975	**22:38:40**	0.3085	26.8458	**23:38:40**	0.4366	3.2992
6:39:20	0.4720	0.6012	**7:39:20**	0.4037	0.4422	**22:39:20**	0.5244	7.3894	**23:39:20**	0.4061	4.0616
6:40:00	0.4683	0.8611	**7:40:00**	0.3902	0.8064	**22:40:00**	0.4293	13.1069	**23:40:00**	0.4988	2.1554
6:40:40	0.3427	1.9648	**7:40:40**	0.4549	0.6896	**22:40:40**	0.3341	16.2280	**23:40:40**	0.5329	2.3478
6:41:20	0.4061	1.3374	**7:41:20**	0.4854	0.5130	**22:41:20**	0.2963	21.3065	**23:41:20**	0.5000	1.7555
6:42:00	0.4049	1.2297	**7:42:00**	0.5171	0.5234	**22:42:00**	0.4927	8.0425	**23:42:00**	0.4976	0.0088
6:42:40	0.3927	1.4957	**7:42:40**	0.4841	0.5173	**22:42:40**	0.1927	63.4524	**23:42:40**	0.4012	5.6605
6:43:20	0.4024	1.2875	**7:43:20**	0.3598	1.0306	**22:43:20**	0.3963	15.3566	**23:43:20**	0.3390	8.2687
6:44:00	0.3720	1.4174	**7:44:00**	0.5463	0.4630	**22:44:00**	0.3000	23.3823	**23:44:00**	0.4195	3.1626
6:44:40	0.3183	2.0349	**7:44:40**	0.4049	0.7194	**22:44:40**	0.4963	8.1385	**23:44:40**	0.4951	3.3162
6:45:20	0.4207	1.1236	**7:45:20**	0.3171	1.2954	**22:45:20**	0.4024	14.8203	**23:45:20**	0.4707	3.9290
6:46:00	0.3220	2.2199	**7:46:00**	0.3500	1.0781	**22:46:00**	0.4878	10.2442	**23:46:00**	0.4415	5.8781
6:46:40	0.3195	2.3760	**7:46:40**	0.3622	0.7031	**22:46:40**	0.3732	16.2472	**23:46:40**	0.4683	2.0743
6:47:20	0.5622	0.7831	**7:47:20**	0.3829	0.4212	**22:47:20**	0.3439	18.0537	**23:47:20**	0.4220	2.9881
6:48:00	0.5829	0.7029	**7:48:00**	0.3878	0.1591	**22:48:00**	0.4988	8.8337	**23:48:00**	0.3573	4.5288
6:48:40	0.4780	0.9555	**7:48:40**	0.4134	0.3327	**22:48:40**	0.4780	9.9760	**23:48:40**	0.3683	2.5908
6:49:20	0.2805	3.2716	**7:49:20**	0.4341	0.4975	**22:49:20**	0.3793	16.5336	**23:49:20**	0.3049	7.5396
6:50:00	0.5573	0.7413	**7:50:00**	0.3110	1.3143	**22:50:00**	0.4976	9.0322	**23:50:00**	0.5646	2.1555
6:50:40	0.4866	0.9445	**7:50:40**	0.3134	0.7482	**22:50:40**	0.4768	7.8531	**23:50:40**	0.5220	3.8395
6:51:20	0.4427	1.1991	**7:51:20**	0.3402	0.3061	**22:51:20**	3.4866	0.1823	**23:51:20**	0.5012	3.1920
6:52:00	0.4634	0.9972	**7:52:00**	0.4573	0.4230	**22:52:00**	0.4049	14.0676	**23:52:00**	0.4341	4.2672
6:52:40	0.3963	1.5304	**7:52:40**	0.4134	0.5748	**22:52:40**	0.4780	11.2121	**23:52:40**	0.4988	2.9293
6:53:20	0.5427	0.6088	**7:53:20**	0.4732	0.4956	**22:53:20**	0.4341	12.5659	**23:53:20**	0.4768	3.6273
6:54:00	0.5000	0.9761	**7:54:00**	0.4829	0.5465	**22:54:00**	0.4671	10.6413	**23:54:00**	0.4439	4.3988
6:54:40	0.4890	0.5801	**7:54:40**	0.4951	0.8083	**22:54:40**	0.4561	10.7217	**23:54:40**	0.4805	4.4620
6:55:20	0.1012	8.6571	**7:55:20**	0.5122	0.6782	**22:55:20**	0.5000	8.8713	**23:55:20**	0.3622	9.5756
6:56:00	0.3463	0.5793	**7:56:00**	0.4402	1.0423	**22:56:00**	0.4817	10.8613	**23:56:00**	0.4963	5.3018
6:56:40	0.3768	0.4096	**7:56:40**	0.5634	0.5169	**22:56:40**	0.4012	16.1400	**23:56:40**	0.3854	9.8186
6:57:20	0.5317	0.3595	**7:57:20**	0.5171	0.5234	**22:57:20**	0.3317	17.4559	**23:57:20**	0.4317	7.8382
6:58:00	0.4134	0.7807	**7:58:00**	0.2488	3.2157	**22:58:00**	0.2890	25.3230	**23:58:00**	0.4268	6.7602
6:58:40	0.2598	0.6046	**7:58:40**	0.5390	0.8464	**22:58:40**	0.2000	49.6325	**23:58:40**	0.4451	5.3879
6:59:20	0.4098	0.8147	**7:59:20**	0.5927	0.5992	**22:59:20**	0.3659	17.5262	**23:59:20**	0.5720	3.5564
7:00:00	0.4098	0.8147	**8:00:00**	0.5927	0.5992	**23:00:00**	0.3659	17.5262	**0:00:00**	0.5720	3.5564

9 EMPIRICAL CDF ANALYSIS

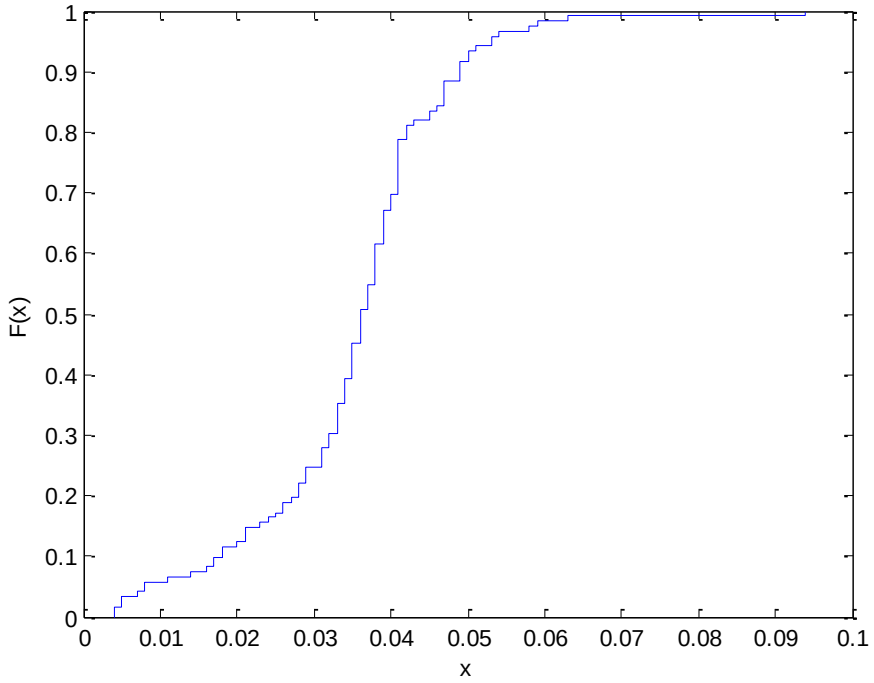


Figure 26 - Empirical CDF 2011 Data

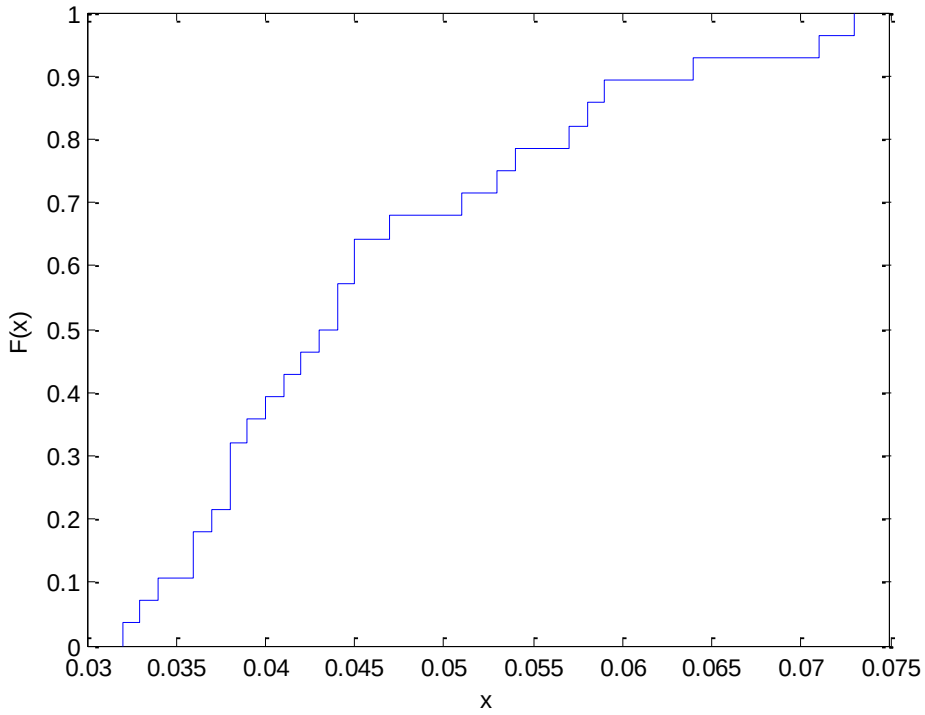


Figure 27 - Empirical CDF 2012 Data

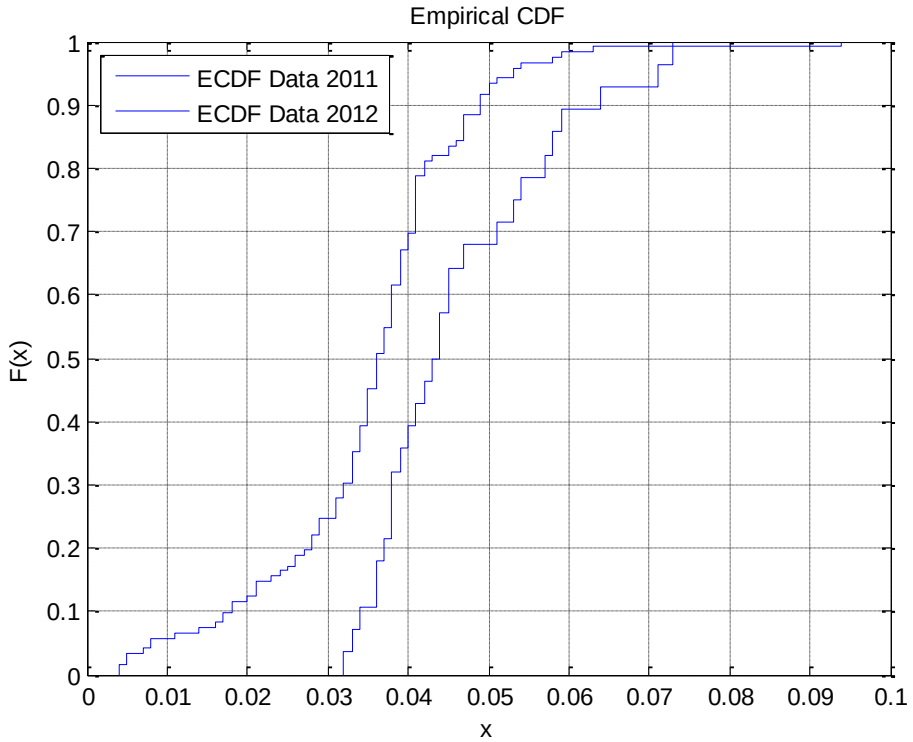


Figure 28 - ECDF of 2011 (Upper) and 2012 (Lower) Data

Data consists of absolute values of (A – C) for both years. All available data was used. If random variable X2011 corresponds to 2011 data and random variable Y2012 to 2012 data, it is clear from the above figure that

P{X2011 ≤ a} ≥ P{Y2012 ≤ a} for any a;

This implies:

P{Y2012 > a} ≥ P{X2011 > a} for any a;

meaning that Y2012 stochastically dominates X2011. This fact implies that all moments of Y2012 (including the mean) are above the corresponding moments of X2011. We can conclude, then, that |(C-A)| is (statistically) larger for 2012 than for 2011. In other words, frequency response deteriorates in 2012 in comparison with 2011.

The following figure includes for 2011 only data corresponding to the first 6 months. Notice that the conclusions of the above analysis remain the same.

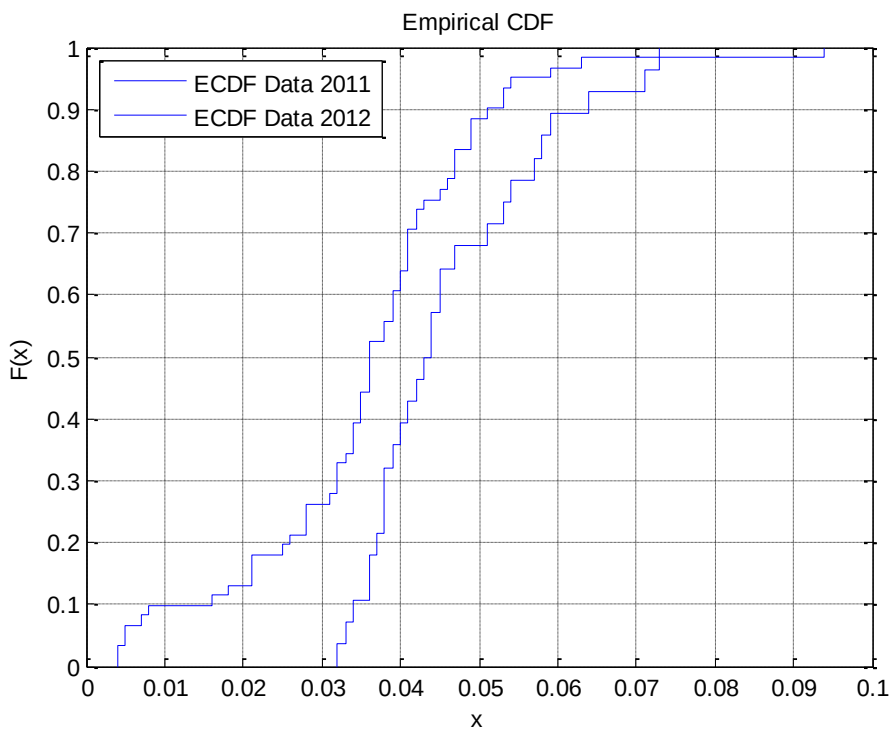


Figure 29 - ECDF using only data from January until June for 2011 and 2012

10 GRID RELIABILITY PERFORMANCE MONITORING DISPLAYS

10.1 Alarms, Alerts and Reports Notification Processes

Figure 17 shows the notifications for users will take place in 3 levels: first identification of frequency event alarms, voltage events alarms, and angle-across-system alarms. NERC criteria and CERTS research results will be used for identifying the alarms that will be broadcasted automatically and the reliability performance report will be routed automatically or on demand.

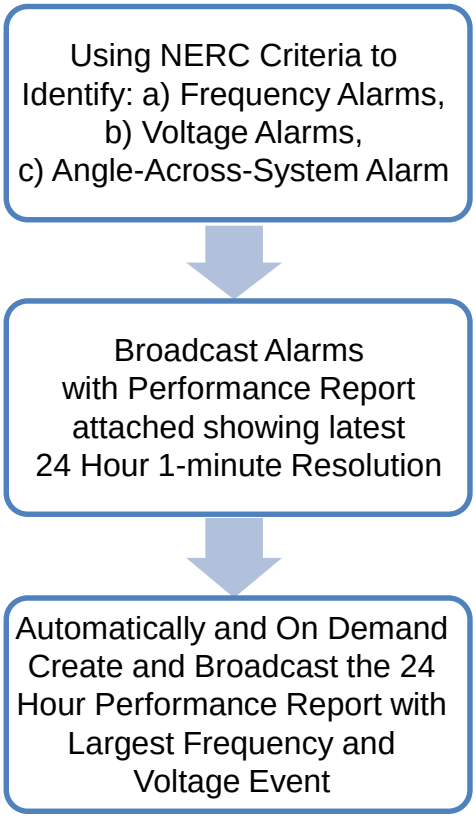


Figure 30 - Alarms, Alerts and Reports Notification Processes

10.2 Interactive Reliability Monitoring Display

Once users get an event notification, they can go to the interactive display shown in Figure 18. On the top-right window they can get the frequency event details, from the bottom-right window they can get the details for voltage events, and in the left window they can track the voltage indices for stations of MISO key transmission lines. All 3 displays will roll automatically on time and the users can stop or rewind them as they need.

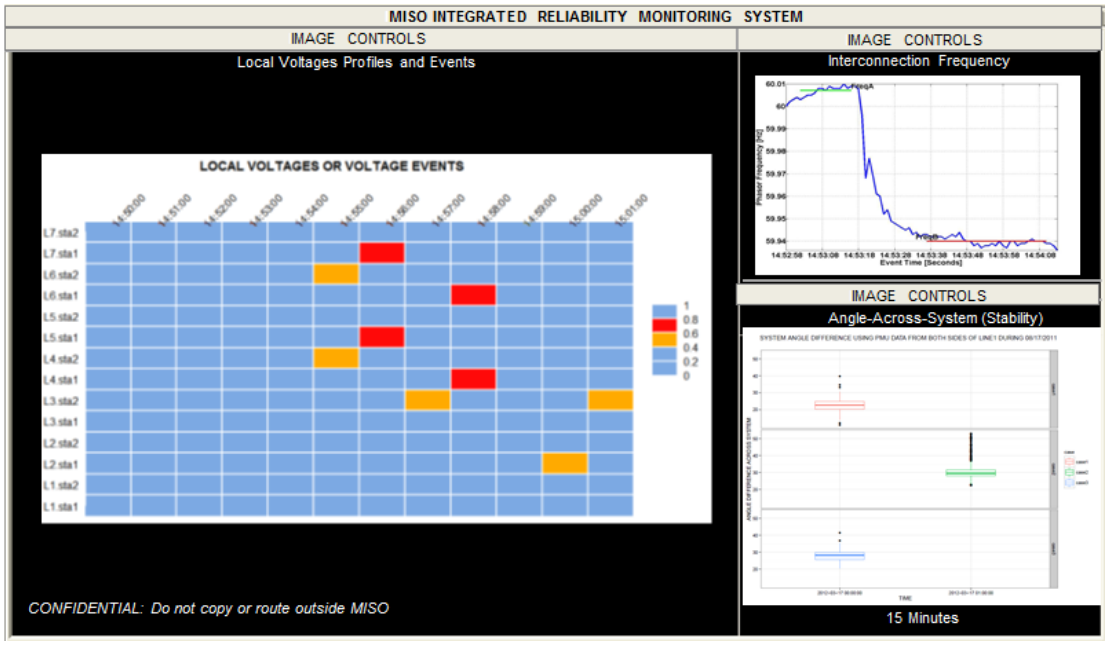


Figure 31 - Interactive Reliability Monitoring Display

11 DAILY RELIABILITY PERFORMANCE REPORT

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. 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 and Current-Time profiles for the largest voltage event of the day
- Estimation of Voltage-Current and other key parameters for largest voltage event

Grid Adequacy Performance Section:

- Summary table with largest stability, voltage and thermal margins for key MISO BPS transmission lines.
- Statistical performance boxplot charts for the voltage and current profiles at key transmission lines.

See Figure 32 and Figure 33 for a sample template of the 2-column format for the daily report using real 2012 data. Each of the report tables and graphs will be organized using a maximum number of 2-column pages with three sections organized in a pre-defined sequence, and including brief textual descriptions for each table and chart component. The Report contains three sections:

- Introduction
- Largest Frequency and Voltage Events of The Day Section
- MISO Grid Adequacy Performance Section

MISO ***DAILY RELIABILITY PERFORMANCE REPORT***

Report from: 03/02/12 12:00 AM
to 03/02/12 11:59 PM Page: 1

1. INTRODUCTION

The objective of this report is to provide automatically daily summaries, or on demand with the latest 24-hours, 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 Section:

- Frequency-Time profile for the largest frequency event of the day
- Estimation of Frequency Response and key parameters for largest frequency event
- Voltage-Time and Current-Time profiles for the largest voltage event of the day
- Estimation of Voltage-Current and other key parameters for largest voltage event

Grid Adequacy Performance Section:

- Summary table with largest stability, voltage and thermal margins for key MISO BPS transmission lines
- Statistical performance boxplot charts for the voltage and current profiles at key transmission lines.

2. LARGEST FREQUENCY AND VOLTAGE EVENT 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.

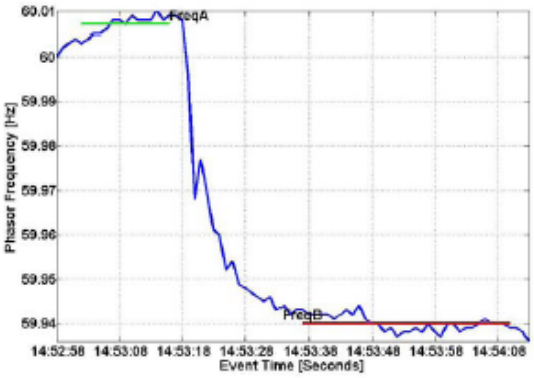


Fig 1 - 1-Second Frequency-Time Graph (Extend to 5 Minutes)

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 load-generation control 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 14:53 EST disturbance on 03/02/12.

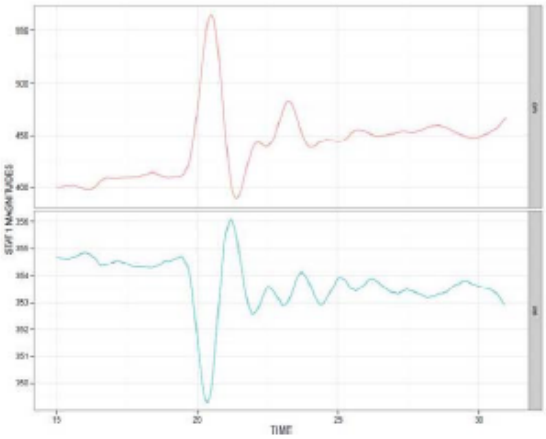


Fig 2 - Voltage -Current Profiles for Largest Event on 03/02/12 at 14:53 EST

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Figure 32 - Daily Report Template – Page 1

MISO ***DAILY RELIABILITY PERFORMANCE REPORT***

Report from: 03/02/12 12:00 AM
to 03/02/12 11:59 PM Page: 2

2.3 Largest Voltage Event Data - Esimated Response

Table with significant voltage-current event parameters during the 14:53 event on 03/02/12 (RESEARCH IN PROGRESS)

Voltage-Current Event Parameters		
Perf. Parameter	Value	Threshold
Lowest Voltage	349.2 KV	TBD
Highest Current	560 Amp	TBD
Delta Voltage	5.3 KV	TBD
Delta Current	160 Amp	TBD
TBD	TBD	TBD
TBD	TBD	TBD

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.

MISO Grid Performance Margins					
Hour	MISO Transmis-sion Line	ANGLE MARGIN	VOLTAGE MARGIN	THERMAL MARGIN	Observa-tions
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.

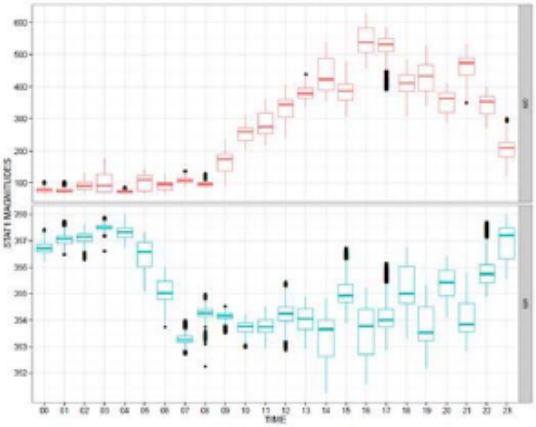

Fig 3 - Voltage-Current Distribution For Each Hour of the Day fot STA1

(SPACE FOR FUTURE RELIABILITY PERFORMANCE INFORMATION AND PLOTS UNDER RESEARCH)

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Figure 33 - Daily Report Template – Page 2

11.1 Major MISO Transmission Line Performance Metrics

Table 2 shows the summary of MISO Grid performance metrics.

Table 5 – Summary of MISO Grid Performance Metrics

MISO Grid Performance Metrics					
Hour	**MISO Transmission Line**	**Angle Margin**	**Voltage Margin**	**Thermal Margin**	**Observations**
22	STA1 - 2	0.309	0.118	NA	
12	STA2 - 3	0.309	0.118	NA	
5	STA3 - 4	0.309	0.118	NA	
18	STA4 - 5	0.309	0.118	NA	
20	STA5 - 6	0.309	0.118	NA	
23	STA6 - 7	0.309	0.118	NA	

12 PROTOTYPE IMPLEMENTATION PLAN AND SCHEDULE

The following table lists all the major activities and provides estimates for major tasks for completing prototype development and Filed Test on or before September 15, 2012.

Table 6 - RPM Development and Field Test Time Table

No.	Development Activity	Est. Comp. Date
1	Functional Specification Completion	4/20/2012
2	Prototype Deployment Completion at MISO	5/30/2012
3	Complete Field Test – MISO, ASR, U. Illinois	8/24/2012
4	Final Report, Conclusions, Recommendations	9/14/2012

APPENDIX-A – ANGLE ACROSS SYSTEM - CASES

Angle Difference Across System is a manifest system performance metric. Modeless algorithm could provide angle difference across system based on PMU data in real time. The whole PMU data file is too large. The following three cases demonstrate the angle difference across system during three time periods, as examples.

Case 1

The time period is the first 1 minute from (1st time point) 2011-08-17T00:00:00.000-05:00 to (1800th time point) 2011-08-17T00:00:59.967-05:00. The angle difference across system is shown in figure 9.

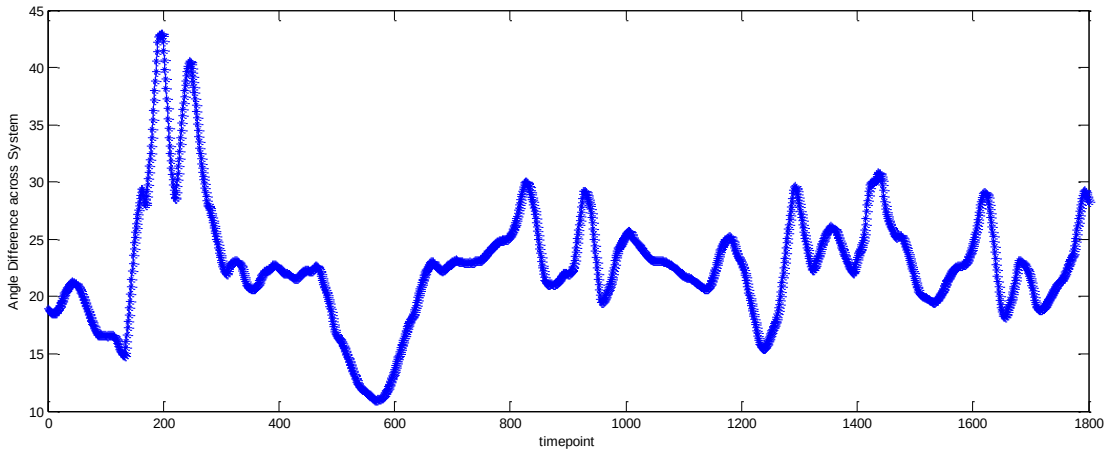

Figure 34 – Angle Difference Across System – Case 1

The angle difference across system is around 23 degree, which is consistent with our hypothesis about system stability metrics.

The exact values at certain time points are shown in the table below.

Table 7 – Exact Values at Certain Time Points – Case 1

	datetime	STA2VM	STA2VA	STA2to	STA2to	STA1VM	STA1VA	STA1to	STA1to	AngleD
1	2011-08-17T00:00:00.000-05:00	357.24	173.776	186	-15	357.9736	174.3894	183.6698	-6.16126	18.92575
31	2011-08-17T00:00:01.000-05:00	357.32	-176.952	185.2	-5.848	358.0569	-176.342	182.8202	3.031211	20.48291
61	2011-08-17T00:00:02.000-05:00	357.16	-167.256	188.4	3.976	357.9068	-166.635	186.0437	12.69936	19.90423
91	2011-08-17T00:00:03.000-05:00	357.32	-157.888	188.4	13.752	358.0393	-157.266	186.2469	22.47912	16.60351
121	2011-08-17T00:00:04.000-05:00	357.36	-147.392	184.8	23.504	358.1082	-146.784	182.3217	32.40352	15.94936
151	2011-08-17T00:00:05.000-05:00	357.28	-136.08	188.8	35.272	358.0209	-135.457	186.4985	43.97969	25.16689
181	2011-08-17T00:00:06.000-05:00	357.24	-125.112	187.6	46.056	357.9864	-124.494	185.2217	54.8188	34.62835
211	2011-08-17T00:00:07.000-05:00	357.36	-113.592	188.8	57.728	358.1029	-112.969	186.4826	66.43766	33.12311
241	2011-08-17T00:00:08.000-05:00	357.24	-101.784	188.8	69.52	357.9841	-101.161	186.4746	78.22671	39.64558
271	2011-08-17T00:00:09.000-05:00	357.2	-90.104	191.2	81.584	357.9316	-89.4722	189.0366	90.17958	29.81416
301	2011-08-17T00:00:10.000-05:00	357.4	-77.464	188.4	93.608	358.1573	-76.8435	185.9639	102.3372	22.99256
331	2011-08-17T00:00:11.000-05:00	357.08	-65.336	194.4	106.496	357.8193	-64.6931	192.2703	114.9463	22.92834
361	2011-08-17T00:00:12.000-05:00	357.16	-53.296	189.6	117.904	357.9157	-52.6708	187.213	126.5717	20.89701
391	2011-08-17T00:00:13.000-05:00	357.2	-41.136	188.8	129.904	357.9619	-40.5139	186.3431	138.6096	22.76941
421	2011-08-17T00:00:14.000-05:00	357.08	-29.36	195.2	142.672	357.8098	-28.7139	193.1605	151.0873	21.78782
451	2011-08-17T00:00:15.000-05:00	357	-17.264	193.2	154.352	357.7477	-16.6255	190.9768	162.8533	22.27486
481	2011-08-17T00:00:16.000-05:00	356.96	-5.408	200.8	167.288	357.6724	-4.74135	199.0278	175.4636	20.43381
511	2011-08-17T00:00:17.000-05:00	357.12	6.504	193.2	178.28	357.8566	7.142755	191.0565	-173.216	15.65988
541	2011-08-17T00:00:18.000-05:00	357.08	18.072	195.2	-169.936	357.8125	18.71801	193.1406	-161.521	12.03628
571	2011-08-17T00:00:19.000-05:00	357.12	30.192	193.6	-157.92	357.851	30.83239	191.5076	-149.434	11.02573
601	2011-08-17T00:00:20.000-05:00	357.08	42.408	197.6	-145.36	357.8086	43.06257	195.6326	-137.048	13.82199
631	2011-08-17T00:00:21.000-05:00	357.04	54.704	193.2	-133.52	357.7767	55.3429	191.0565	-125.018	18.30345
661	2011-08-17T00:00:22.000-05:00	357.04	66.544	201.2	-120.928	357.7665	67.21132	199.3399	-112.767	22.90171
691	2011-08-17T00:00:23.000-05:00	357.16	78.528	195.6	-109.264	357.8796	79.17581	193.6436	-100.864	22.65208
721	2011-08-17T00:00:24.000-05:00	357.04	90.784	197.2	-97.288	357.7879	91.43644	195.0858	-88.9594	22.97683
751	2011-08-17T00:00:25.000-05:00	356.84	102.84	204	-84.088	357.5416	103.5185	202.3801	-76.0447	23.27503
781	2011-08-17T00:00:26.000-05:00	357	114.904	198.4	-72.76	357.7255	115.5616	196.4753	-64.4834	24.86156
811	2011-08-17T00:00:27.000-05:00	356.88	126.752	204.4	-60.128	357.58	127.4319	202.7998	-52.0997	26.80309
841	2011-08-17T00:00:28.000-05:00	356.96	139.128	199.6	-48.512	357.6902	139.7897	197.6738	-40.2864	27.76331
871	2011-08-17T00:00:29.000-05:00	356.92	151.088	204	-35.752	357.6151	151.7666	202.424	-27.7072	21.13226
901	2011-08-17T00:00:30.000-05:00	356.96	163.208	204	-23.56	357.6498	163.8867	202.4599	-15.5145	21.98862
931	2011-08-17T00:00:31.000-05:00	356.84	175.6	205.6	-11.224	357.542	176.284	204.0149	-3.24379	29.08007
961	2011-08-17T00:00:32.000-05:00	357.16	-172	199.2	0.776	357.8583	-171.339	197.4856	9.021992	19.64399
991	2011-08-17T00:00:33.000-05:00	357	-159.136	199.6	13.448	357.7142	-158.474	197.7853	21.67414	24.60174
1021	2011-08-17T00:00:34.000-05:00	357.12	-146.04	191.2	25.464	357.8642	-145.409	188.9449	34.05774	24.56504
1051	2011-08-17T00:00:35.000-05:00	357.08	-132.616	193.6	39.04	357.8271	-131.976	191.392	47.52551	23.11268
1081	2011-08-17T00:00:36.000-05:00	356.76	-118.24	206.8	55.496	357.4264	-117.55	205.4807	63.4261	22.65323
1111	2011-08-17T00:00:37.000-05:00	356.52	-103.552	210.4	70.456	357.1834	-102.849	209.1786	78.24385	21.62407
1141	2011-08-17T00:00:38.000-05:00	356.8	-90.568	203.6	82.664	357.4879	-89.8903	202.0639	90.72176	20.70865
1171	2011-08-17T00:00:39.000-05:00	357.12	-76.112	193.6	95.816	357.8483	-75.4715	191.5275	104.3023	24.88701
1201	2011-08-17T00:00:40.000-05:00	356.6	-61.248	207.2	112.288	357.2834	-60.5572	205.7768	120.2	22.77238
1231	2011-08-17T00:00:41.000-05:00	356.76	-46.072	202.8	126.944	357.4597	-45.3975	201.165	135.0334	15.98757
1261	2011-08-17T00:00:42.000-05:00	356.72	-31.272	205.6	142.136	357.405	-30.5871	204.1301	150.1128	18.21048
1291	2011-08-17T00:00:43.000-05:00	356.84	-16.352	198.8	156.584	357.5251	-15.691	197.1692	164.8388	29.52208
1321	2011-08-17T00:00:44.000-05:00	356.76	-1.96	202	171.312	357.4371	-1.28739	200.5009	179.4327	22.44393
1351	2011-08-17T00:00:45.000-05:00	356.96	12.816	200	-174.184	357.6465	13.48089	198.3879	-165.976	25.93332
1381	2011-08-17T00:00:46.000-05:00	356.72	28.152	205.6	-158.208	357.3878	28.83758	204.2454	-150.232	23.2097
1411	2011-08-17T00:00:47.000-05:00	356.64	42.456	208.8	-143.472	357.2909	43.15349	207.6269	-135.622	25.14819
1441	2011-08-17T00:00:48.000-05:00	356.92	56.776	198.4	-130.496	357.6178	57.43493	196.6703	-122.222	30.49242
1471	2011-08-17T00:00:49.000-05:00	356.84	70.88	200.8	-115.984	357.5209	71.54812	199.2465	-107.812	25.32157
1501	2011-08-17T00:00:50.000-05:00	356.76	85.272	200.8	-101.992	357.4697	85.93913	199.0474	-93.8211	21.24587
1531	2011-08-17T00:00:51.000-05:00	356.56	98.776	208	-87.288	357.2174	99.47063	206.7673	-79.409	19.52387
1561	2011-08-17T00:00:52.000-05:00	356.92	111.616	197.6	-75.496	357.6024	112.2728	195.9589	-67.1889	21.99154
1591	2011-08-17T00:00:53.000-05:00	356.76	123.688	202.8	-62.984	357.437	124.3634	201.3201	-54.8956	23.26219
1621	2011-08-17T00:00:54.000-05:00	357.04	136.008	195.2	-51.552	357.7413	136.6554	193.3636	-43.1384	29.12184
1651	2011-08-17T00:00:55.000-05:00	356.72	148.264	202.8	-38.32	357.3906	148.9397	201.3638	-30.2328	18.62172
1681	2011-08-17T00:00:56.000-05:00	356.84	160.088	199.6	-26.976	357.5292	160.7516	197.9603	-18.7544	23.1701
1711	2011-08-17T00:00:57.000-05:00	356.68	172.552	210	-13.536	357.3486	173.2529	208.7353	-5.72939	19.01045
1741	2011-08-17T00:00:58.000-05:00	356.72	-175.008	209.6	-0.88	357.3704	-174.308	208.4468	6.94146	20.65339
1771	2011-08-17T00:00:59.000-05:00	356.56	-162.464	214.4	11.96	357.21	-161.747	213.3459	19.60142	23.5169

Case 2

The time period is 1 minute from (187573rd time point) 2011-08-17T01:44:29.000 to (188798th time point) 2011-08-17T01:45:09.833-05:00. The angle difference across system is shown figure 10.

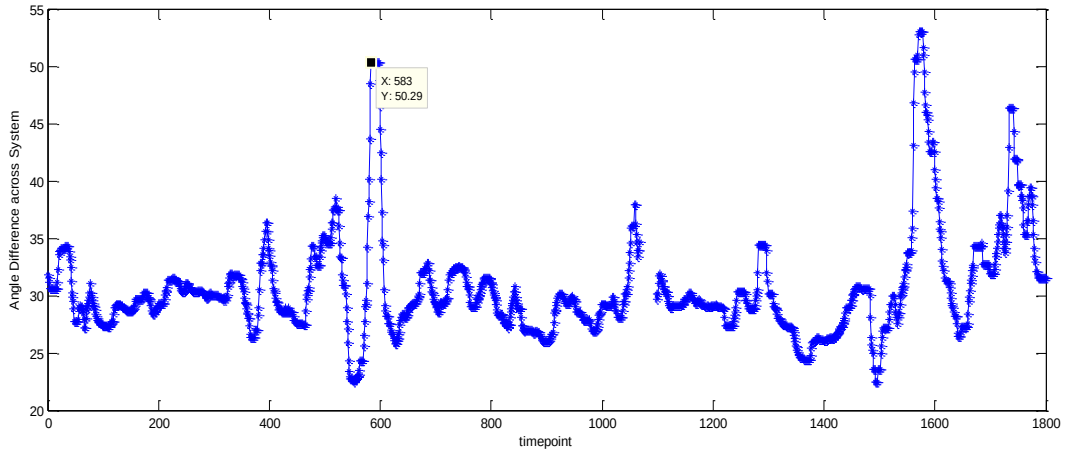

Figure 35 – Angle Difference Across System - Case 2

Comparing case 1 and case 2, it's very easy to show that angle difference across system is a significant system performance metric. In case 1 and case 2, although the voltage magnitude and angle difference don't change very much (thus, they are not good system metrics), since the current increase from around 200A to 350A, the system profile changes a lot. Meanwhile, the angle difference across system changes from around 23 degree to 30 degree, which is consistent with system variation.

The exact values at certain time points are shown in the table below.

Table 8 - Exact Values at Certain Time Points – Case 2

	datetime	STA2VM	STA2VA	STA2to	STA2to	STA1VM	STA1VA	STA1to	STA1toSTA2IA	AngleDifferenceA
186999	2011-08-17T01:44:09.867-05:00	357.88	-53.904	380.8	127.448	358.3439	-52.6158	382.2266	131.741659	31.81981811
187029	2011-08-17T01:44:10.867-05:00	358.2	-53.24	380.4	128.36	358.628	-51.9538	381.9538	132.660091	34.11792545
187059	2011-08-17T01:44:11.867-05:00	358.24	-51.368	370	129.344	358.7662	-50.119	371.1514	133.7712235	29.00383498
187089	2011-08-17T01:44:12.867-05:00	358.2	-49.176	372	131.768	358.6995	-47.9195	373.2589	136.1694556	27.75418867
187119	2011-08-17T01:44:13.867-05:00	358.36	-46.2	368	134.536	358.8779	-44.958	369.1719	138.9884509	28.96737727
187149	2011-08-17T01:44:14.867-05:00	358.12	-43.816	378.8	137.536	358.5791	-42.5354	380.2358	141.855051	28.69294584
187179	2011-08-17T01:44:15.867-05:00	358.84	-40.848	361.2	139.72	359.363	-39.6308	362.3182	144.2629847	29.81951466
187209	2011-08-17T01:44:16.867-05:00	358.12	-38.192	371.6	142.752	358.6186	-36.9366	372.8598	147.1571855	29.69986432
187239	2011-08-17T01:44:17.867-05:00	358.56	-35.944	364.4	144.896	359.055	-34.7145	365.639	149.3939064	30.37756869
187269	2011-08-17T01:44:18.867-05:00	358.4	-32.92	364.8	147.696	358.926	-31.6892	365.9248	152.1886076	30.36924973
187299	2011-08-17T01:44:19.867-05:00	358.44	-30.336	368.8	150.656	358.9251	-29.091	370.0968	155.0980061	30.03345597
187329	2011-08-17T01:44:20.867-05:00	358.48	-26.992	365.2	153.656	359.0027	-25.76	366.3398	158.1444893	31.91072901
187359	2011-08-17T01:44:21.867-05:00	358	-23.736	375.2	157.536	358.4622	-22.4673	376.6084	161.8953582	28.3823798
187389	2011-08-17T01:44:22.867-05:00	358.48	-20.984	366.8	159.856	358.9808	-19.7462	368.0291	164.3236724	34.83596643
187419	2011-08-17T01:44:23.867-05:00	358.52	-18.344	364.4	162.368	359.0321	-17.1147	365.575	166.8663292	28.7224865
187449	2011-08-17T01:44:24.867-05:00	358.4	-14.256	365.6	166.384	358.9248	-13.0224	366.7337	170.8666698	27.57295717
187479	2011-08-17T01:44:25.867-05:00	358.28	-10.152	369.2	170.696	358.7858	-8.90543	370.4224	175.1322951	33.36806583
187509	2011-08-17T01:44:26.867-05:00	358.56	-5.952	368	175.064	359.0399	-4.71001	369.3127	179.5169034	35.02367142
187539	2011-08-17T01:44:27.867-05:00	358.52	-1.232	365.2	179.472	359.0351	-2.53E-05	366.3679	-176.039407	27.12764243
187569	2011-08-17T01:44:28.867-05:00	358.44	3.536	366.8	-175.608	358.9387	4.773989	368.0368	-171.1409383	26.4842845
187599	2011-08-17T01:44:29.867-05:00	358.32	8.136	371.6	-170.776	358.7988	9.391071	372.9329	-166.3694144	42.46430606
187629	2011-08-17T01:44:30.867-05:00	358.28	12.88	371.6	-165.824	358.7305	14.1357	373.036	-161.4194594	26.28816168
187659	2011-08-17T01:44:31.867-05:00	358.16	18.128	374.8	-160.424	358.5969	19.39522	376.2986	-156.0594182	29.3030517
187689	2011-08-17T01:44:32.867-05:00	358.4	22.952	372	-155.728	358.848	24.20868	373.4474	-151.3268826	31.37851303
187719	2011-08-17T01:44:33.867-05:00	358.36	28.416	369.2	-150.56	358.8418	29.66272	370.5105	-146.1239936	29.78307953
187749	2011-08-17T01:44:34.867-05:00	358.2	33.76	372.8	-145.04	358.6664	35.01979	374.1832	-140.6497932	32.17158601
187779	2011-08-17T01:44:35.867-05:00	358.6	39.016	367.2	-139.992	359.0812	40.25511	368.5041	-135.5287867	30.54336799
187809	2011-08-17T01:44:36.867-05:00	358.28	45.2	373.6	-133.664	358.7569	46.46204	374.9489	-129.2816872	28.43152638
187839	2011-08-17T01:44:37.867-05:00	358.4	50.656	374.4	-127.952	358.8435	51.92091	375.8742	-123.5794499	30.3006331
187869	2011-08-17T01:44:38.867-05:00	358.32	55.824	371.2	-123.072	358.7957	57.07777	372.5424	-118.6608151	27.03489062
187899	2011-08-17T01:44:39.867-05:00	358.48	61.28	367.2	-117.856	358.9786	62.51921	368.4395	-113.3933363	25.93812271
187929	2011-08-17T01:44:40.867-05:00	358.2	66.84	372.4	-112.176	358.695	68.09792	373.6773	-107.7795281	29.77001319
187959	2011-08-17T01:44:41.867-05:00	358.24	72.352	376	-106.208	358.6806	73.62296	377.4908	-101.8562248	28.55591706
187989	2011-08-17T01:44:42.867-05:00	358.44	77.896	369.2	-101.072	358.9207	79.14247	370.5151	-96.63506867	27.2836838
188019	2011-08-17T01:44:43.867-05:00	358.12	82.936	379.6	-95.512	358.5531	84.21973	381.1322	-91.20349685	29.81937393
188049	2011-08-17T01:44:44.867-05:00	358.28	88.352	372.8	-90.544	358.7595	89.61128	374.136	-86.15211009	34.53889
188079	2011-08-17T01:44:45.867-05:00	358.24	92.928	375.2	-85.808	358.7031	94.19586	376.6063	-81.44567937	NaN
188109	2011-08-17T01:44:46.867-05:00	358.4	97.472	372	-81.52	358.8906	98.72794	373.2922	-77.11656257	30.81920922
188139	2011-08-17T01:44:47.867-05:00	358.16	102.304	375.6	-76.504	358.634	103.5733	376.9684	-72.14672887	29.12627224
188169	2011-08-17T01:44:48.867-05:00	358.52	107.224	368.8	-71.808	359.0083	108.4687	370.0854	-67.36483342	29.31206352
188199	2011-08-17T01:44:49.867-05:00	358.12	112.016	374.8	-66.776	358.59	113.2828	376.179	-62.41009243	29.1288037
188229	2011-08-17T01:44:50.867-05:00	358.44	117.184	372.8	-61.6	358.904	118.443	374.193	-57.20699086	27.40500727
188259	2011-08-17T01:44:51.867-05:00	358.24	122.744	375.2	-56.08	358.7152	124.0116	376.5625	-51.71702899	29.55721294
188289	2011-08-17T01:44:52.867-05:00	358.16	128.248	381.6	-50.032	358.5738	129.5387	383.2087	-45.74673969	34.43418913
188319	2011-08-17T01:44:53.867-05:00	358.28	134.152	375.6	-44.504	358.7329	135.4212	377.0449	-40.14640961	27.94237688
188349	2011-08-17T01:44:54.867-05:00	358.08	140.072	380	-38.4	358.5173	141.3572	381.5185	-34.09629467	25.25369847
188379	2011-08-17T01:44:55.867-05:00	358.44	147.112	370.8	-31.712	358.9048	148.3642	372.1807	-27.2951551	25.9728627
188409	2011-08-17T01:44:56.867-05:00	358.2	154.104	378	-24.504	358.6517	155.3817	379.4592	-20.17520928	26.29951705
188439	2011-08-17T01:44:57.867-05:00	358.48	161.088	366	-18.12	358.9853	162.323	367.2083	-13.64227905	28.937212
188469	2011-08-17T01:44:58.867-05:00	358.24	168.536	374.4	-10.192	358.7001	169.8012	375.8133	-5.820480756	30.64500151
188499	2011-08-17T01:44:59.867-05:00	358.24	175.576	372	-3.288	358.7133	176.8328	373.3547	1.112548699	23.60980385
188529	2011-08-17T01:45:00.867-05:00	358.24	-177.56	375.2	3.8	358.6898	-176.292	376.654	8.161599636	28.07976984
188559	2011-08-17T01:45:01.867-05:00	358.32	-170.48	371.2	10.6	358.799	-169.226	372.5305	15.01136174	43.1268741
188589	2011-08-17T01:45:02.867-05:00	358.2	-163.904	374.8	17.336	358.6655	-162.637	376.1955	21.70263931	42.52595893
188619	2011-08-17T01:45:03.867-05:00	358.28	-157.52	375.6	23.872	358.7263	-156.251	377.0687	28.22922701	31.26180972
188649	2011-08-17T01:45:04.867-05:00	358.24	-150.608	375.2	30.584	358.713	-149.34	376.5705	34.94685351	27.27780033
188679	2011-08-17T01:45:05.867-05:00	358.24	-144.944	375.6	36.424	358.6896	-143.675	377.0565	40.78092592	34.32767375
188709	2011-08-17T01:45:06.867-05:00	358.48	-139.304	369.6	41.72	358.9627	-138.056	370.9099	46.15271097	33.6682108
188739	2011-08-17T01:45:07.867-05:00	358.24	-133.904	374	47.248	358.7157	-132.64	375.3551	51.62505377	46.33776411
188769	2011-08-17T01:45:08.867-05:00	358.44	-128.88	372.8	52.36	358.9007	-127.621	374.2049	56.75282931	39.4406305

Case 3

The time period is 1 minute from (40000th time point) 2011-08-17T00:22:29.900-05:00to (41770th time point) 2011-08-17T00:23:28.900-05:00. The angle difference across system is shown in figure 11.

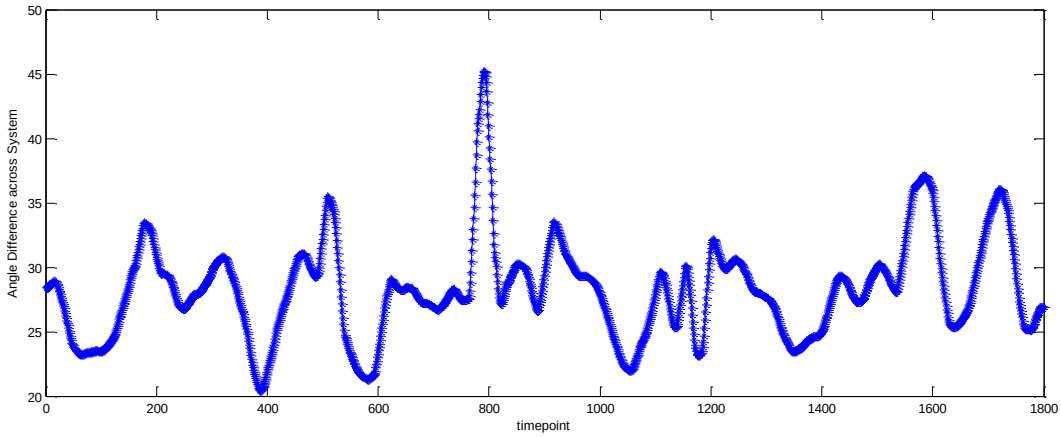

Figure 36 – Angle Difference Across System – Case 3

The exact values at certain time points are shown in the table below.

Table 9 - Exact Values at Certain Time Points – Case 3

	datetime	STA2VM	STA2VA	STA2to	STA2to	STA1VM	STA1VA	STA1to	STA1to	AngleD
40000	2011-08-17T00:22:29.900-05:00	355.32	23.128	303.6	-157.408	355.827	24.15985	304.4074	-152.053	28.37297
40030	2011-08-17T00:22:30.900-05:00	355.72	22.856	295.6	-158.024	356.2411	23.85891	296.2826	-152.516	27.18665
40060	2011-08-17T00:22:31.900-05:00	355.56	23.352	300.4	-157.472	356.0893	24.37167	301.0835	-152.054	23.24678
40090	2011-08-17T00:22:32.900-05:00	355.56	23.384	298.8	-157.296	356.0689	24.39863	299.5631	-151.85	23.53596
40120	2011-08-17T00:22:33.900-05:00	355.36	23.24	304	-157.208	355.8583	24.2733	304.849	-151.86	24.48672
40150	2011-08-17T00:22:34.900-05:00	355.56	23.128	302	-157.248	356.0445	24.15415	302.8964	-151.862	28.82359
40180	2011-08-17T00:22:35.900-05:00	355.36	23.6	305.6	-156.672	355.8431	24.63912	306.5276	-151.353	33.40479
40210	2011-08-17T00:22:36.900-05:00	355.2	23.256	310	-156.64	355.6527	24.31132	311.0897	-151.401	29.55808
40240	2011-08-17T00:22:37.900-05:00	355.48	22.52	306	-157.808	355.9704	23.55999	306.8988	-152.494	26.97269
40270	2011-08-17T00:22:38.900-05:00	355.2	21.768	313.2	-157.92	355.6372	22.83461	314.3763	-152.736	27.9216
40300	2011-08-17T00:22:39.900-05:00	355.48	20.816	303.6	-159.472	355.9593	21.84798	304.5309	-154.116	29.87856
40330	2011-08-17T00:22:40.900-05:00	355.36	19.088	309.6	-160.704	355.7997	20.14173	310.7442	-155.457	29.8801
40360	2011-08-17T00:22:41.900-05:00	355.52	17.32	303.6	-163	356.0028	18.35179	304.5154	-157.643	25.42095
40390	2011-08-17T00:22:42.900-05:00	355.48	15.672	305.6	-164.568	355.9594	16.71084	306.5443	-159.247	20.66124
40420	2011-08-17T00:22:43.900-05:00	355.24	14.072	313.2	-165.6	355.6753	15.13853	314.3845	-160.416	25.92725
40450	2011-08-17T00:22:44.900-05:00	355.2	12.792	315.6	-166.816	355.6341	13.86691	316.804	-161.672	30.28829
40480	2011-08-17T00:22:45.900-05:00	355.32	10.504	309.6	-169.544	355.7888	11.55727	310.6176	-164.296	29.60728
40510	2011-08-17T00:22:46.900-05:00	355.56	8.664	303.6	-171.824	356.0614	9.695276	304.4327	-166.465	35.33474
40540	2011-08-17T00:22:47.900-05:00	355.12	7.256	312.8	-172.624	355.5783	8.321059	313.8831	-167.433	24.45668
40570	2011-08-17T00:22:48.900-05:00	355.28	5.96	312.4	-174.048	355.7517	7.022935	313.4231	-168.847	21.53242
40600	2011-08-17T00:22:49.900-05:00	355.2	4.496	315.6	-175.16	355.6396	5.570797	316.7804	-170.016	23.78759
40630	2011-08-17T00:22:50.900-05:00	355.4	3.376	307.6	-176.68	355.8643	4.422257	308.6243	-171.396	28.54452
40660	2011-08-17T00:22:51.900-05:00	355.28	2.36	314.8	-177.376	355.7267	3.431672	315.9454	-172.217	28.38411
40690	2011-08-17T00:22:52.900-05:00	355.52	1.512	305.6	-178.864	356.0146	2.550406	306.4774	-173.542	27.15725
40720	2011-08-17T00:22:53.900-05:00	355.2	0.656	314.4	-179.072	355.6449	1.726577	315.5507	-173.908	27.40453
40750	2011-08-17T00:22:54.900-05:00	355.4	-0.416	309.6	179.512	355.8714	0.636974	310.6063	-175.238	27.46895
40780	2011-08-17T00:22:55.900-05:00	355.36	-1.616	310	178.44	355.818	-0.56126	311.0672	-176.319	41.53486
40810	2011-08-17T00:22:56.900-05:00	355.32	-1.944	314	178.44	355.7509	-0.87488	315.2088	-176.388	30.77547
40840	2011-08-17T00:22:57.900-05:00	355.28	-1.936	313.2	178.376	355.7171	-0.86963	314.377	-176.439	29.53742
40870	2011-08-17T00:22:58.900-05:00	355.32	-2.992	313.2	177.296	355.7599	-1.9258	314.3654	-177.518	29.06277
40900	2011-08-17T00:22:59.900-05:00	355.8	-3.528	302	175.984	356.2967	-2.50281	302.8427	-178.625	29.93138
40930	2011-08-17T00:23:00.900-05:00	355.4	-3.6	307.6	176.232	355.8769	-2.554	308.569	-178.483	31.91034
40960	2011-08-17T00:23:01.900-05:00	355.6	-3.056	309.6	177.008	356.0558	-2.0033	310.6749	-177.74	29.36452
40990	2011-08-17T00:23:02.900-05:00	355.28	-2.52	314.4	177.88	355.7101	-1.44938	315.6145	-176.955	28.69453
41020	2011-08-17T00:23:03.900-05:00	355.72	-2.616	305.2	177.232	356.1883	-1.579	306.1915	-177.438	24.96508
41050	2011-08-17T00:23:04.900-05:00	355.24	-1.984	314	178.344	355.6774	-0.91477	315.1806	-176.485	22.04394
41080	2011-08-17T00:23:05.900-05:00	355.52	-1.528	307.6	178.656	355.9571	-0.48155	308.7436	-176.061	24.77447
41110	2011-08-17T00:23:06.900-05:00	355.4	-1.336	312	178.912	355.8413	-0.27419	313.1522	-175.881	29.54401
41140	2011-08-17T00:23:07.900-05:00	355.52	-0.896	309.2	179.336	355.9558	0.155963	310.3592	-175.408	26.16948
41170	2011-08-17T00:23:08.900-05:00	355.6	-0.096	302.4	179.344	356.106	0.930942	303.2037	-175.275	23.94044
41200	2011-08-17T00:23:09.900-05:00	355.44	0.608	311.6	-179.288	355.8967	1.668017	312.6835	-174.073	31.75159
41230	2011-08-17T00:23:10.900-05:00	355.44	1.624	309.2	-178.368	355.9012	2.675691	310.2481	-173.112	30.06367
41260	2011-08-17T00:23:11.900-05:00	355.4	1.696	311.2	-178.168	355.852	2.754857	312.3009	-172.947	29.66128
41290	2011-08-17T00:23:12.900-05:00	355.84	1.4	299.6	-179.208	356.343	2.416707	300.3963	-173.773	27.90818
41320	2011-08-17T00:23:13.900-05:00	355.44	1.696	308	-178.352	355.9044	2.74351	309.0265	-173.075	25.95671
41350	2011-08-17T00:23:14.900-05:00	355.64	1.848	304.4	-178.248	356.0999	2.882665	305.4227	-172.905	23.47047
41380	2011-08-17T00:23:15.900-05:00	355.32	1.8	312	-178.08	355.776	2.861761	313.0885	-172.873	24.51592
41410	2011-08-17T00:23:16.900-05:00	355.6	1.28	302	-179.016	356.0756	2.30622	302.9362	-173.63	26.6435
41440	2011-08-17T00:23:17.900-05:00	355.44	1.264	307.2	-178.816	355.9058	2.308734	308.2148	-173.525	29.0958
41470	2011-08-17T00:23:18.900-05:00	355.48	0.912	307.6	-179.224	355.9532	1.957838	308.5854	-173.939	27.40729
41500	2011-08-17T00:23:19.900-05:00	355.48	0.584	304.4	179.944	356.0007	1.617834	305.1529	-174.711	30.14367
41530	2011-08-17T00:23:20.900-05:00	355.4	-0.008	312	-179.928	355.8605	1.053432	313.0693	-174.72	28.16028
41560	2011-08-17T00:23:21.900-05:00	355.44	0.208	306.8	179.784	355.9434	1.250571	307.647	-174.915	35.17128
41590	2011-08-17T00:23:22.900-05:00	355.36	0.456	310.8	-179.712	355.8456	1.512918	311.7526	-174.482	36.80176
41620	2011-08-17T00:23:23.900-05:00	355.48	1.136	306.8	-179.408	355.9968	2.178162	307.588	-174.106	27.90462
41650	2011-08-17T00:23:24.900-05:00	355.36	1	310.8	-179.184	355.8474	2.05688	311.7447	-173.954	25.86815
41680	2011-08-17T00:23:25.900-05:00	355.56	1.176	302.8	-179.488	356.0786	2.204152	303.5499	-174.114	30.15039
41710	2011-08-17T00:23:26.900-05:00	355.32	1.92	312	-178.104	355.7924	2.981428	313.0174	-172.896	35.1634
41740	2011-08-17T00:23:27.900-05:00	355.48	2.936	312	-176.952	355.9367	3.997268	313.0857	-171.743	32.57093
41770	2011-08-17T00:23:28.900-05:00	355.32	3.728	310.4	-176.552	355.8173	4.783418	311.2991	-171.315	25.19523

APPENDIX-B - MISO DATA RESULTS

1. Thermal Margin Reliability Measure
   S^{max} , which is the rated power on this transmission line, is not known to us, hence we cannot obtain this reliability measure. But basically this measure is not critical for high voltage transmission line.

2. Voltage Margin Reliability Measure

Based on the expression of this reliability measure, the lower the value is, the closer the voltage is to nominal voltage.

Time	H_1^v	RMS_1^v	H_2^v	RMS_2^v
0	0.718144928	0.59688014	0.761149983	0.6215522
1	0.838801932	0.702344145	0.889850878	0.727539957
2	0.879768116	0.810741645	0.952092408	0.87773467
3	0.723710145	0.59825493	0.763838371	0.605946615
4	0.677565217	0.614665335	0.706864185	0.631077025
5	0.628560386	0.581695287	0.644884897	0.58998577
6	0.552888889	0.439417762	0.590020637	0.456078109
7	0.494299517	0.441434327	0.540719752	0.464436894
8	0.746434783	0.638505627	0.848482008	0.715255753
9	0.650589372	0.55373979	0.73924895	0.629195434
10	0.628792271	0.585346876	0.716630702	0.663970052
11	0.600193237	0.563203915	0.690288687	0.637116895
12	0.626318841	0.574583573	0.723190974	0.660381614
13	20	1.585920747	20	1.615028515
14	0.611710145	0.567650297	0.682567712	0.633146894
15	0.610164251	0.560432984	0.681666123	0.622387794
16	0.609545894	0.583906036	0.676305661	0.649484205
17	0.634434783	0.591242413	0.712367423	0.657992133
18	0.682666667	0.653780307	0.771895086	0.738536394
19	0.713429952	0.68147779	0.804355045	0.767963514
20	20	1.274959392	20	1.320667378
21	0.760115942	0.71628421	0.844223723	0.792059416
22	0.754705314	0.718275539	0.814664306	0.777873833
23	0.742028986	0.673883842	0.797709712	0.727326305

3. Stability Margin Reliability Measure

Based on the expression of this reliability measure, the lower the value is, the less the stability margin is.

Time Period	H^s	AVG^s
0	0.141349337279839	0.342749143942295
1	0.145259314953378	0.301127371594450
2	0.273787719980096	0.466458264351488
3	0.064879629938307	0.235875650665482
4	0.066056554690988	0.249297552204780
5	0.036502178671083	0.233210637684598
6	0.007703944555625	0.169013525025834
7	0.042078558532169	0.227282623055903
8	0.146230277266041	0.493983819664567
9	0.376025627195878	0.509672037870044
10	0.395032266507353	0.565353230001772
11	-1.462751377796786	0.578255328405010
12	-2.506597635530304	0.539970375620499
13^+	-3.089679349602145	0.362329556392631
14^+	-3.090867743372151	0.148189450115652
15^+	-3.085513991044506	0.598219996698935
16^+	-3.090090513677472	0.311366868582220
17^+	-3.090302103723917	0.224285436764479
18^+	0.435924915037053	0.651164615523481
19^+	0.491455562311329	0.658635265026685
20^+	0.465500756776636	0.647696241465929
21^+	0.399706495380680	0.648524998159992
22^+	0.395439222231580	0.627400256771162
23^+	-3.088586531328708	0.550356481845383

$^+$: The real power flow changes the direction during that hour.

Note:

1. An interesting point about this transmission line, which indicates in this margin measure, is that the power flowing on this line changes the direction during one day. Basically the power flows from Station 1 to Station 2 in the morning and the direction keeps changing in the afternoon. During night from 6:00pm, the power keeps flowing from Station 2 to Station 1. The specific Angle-Across-System values over time are shown in the appendix.
2. Although the changing direction of power flow results in transient states, where Angle-Across-System is abnormally higher and consequently, the H^s even goes to negative, the reliability margin measure can still help us to understand the performance of this transmission line better. For instance, during the morning from 2:00am to 7:00 am, when the power transfers from station 2 to station 1, the loading on this line is much heavier than the afternoon from 6:00pm to 12:00pm. As well, the loading is very heavy during 2:00pm to 3:00pm.
3. To exploit more information from PMU data, more data processing work is in progress.
4. The first excel file (data from 0:00-8:00) missed data from 00:03:19 to 00:03:36, which should be located before 5984th row. Third excel file (from 16:00 to 24:00) also missed data at some time points.

The angle difference across the system during each hour when the H^s is negative

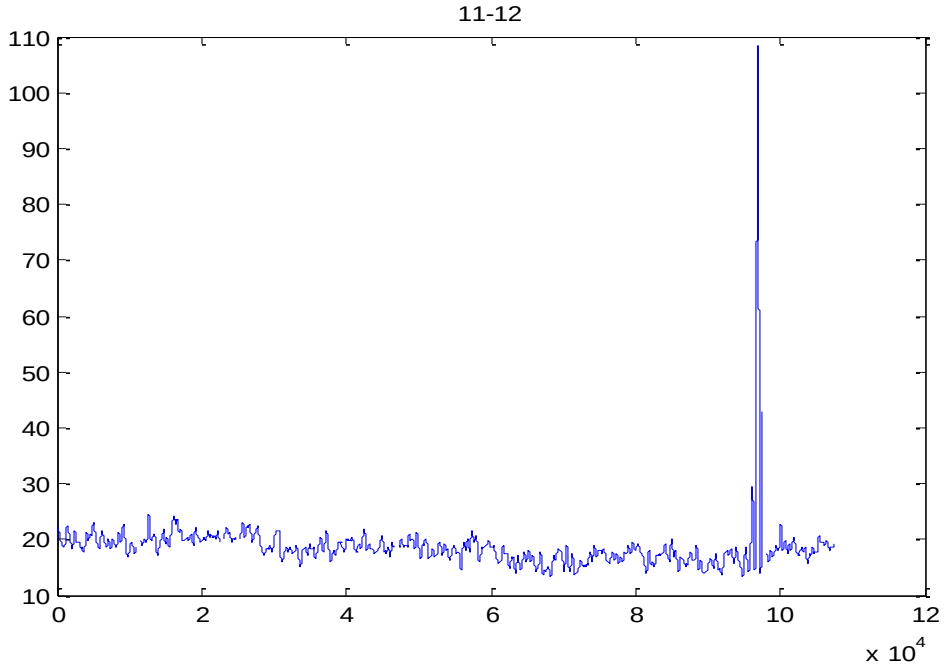

Fig1. Angle-Cross-System during 11:00-12:00

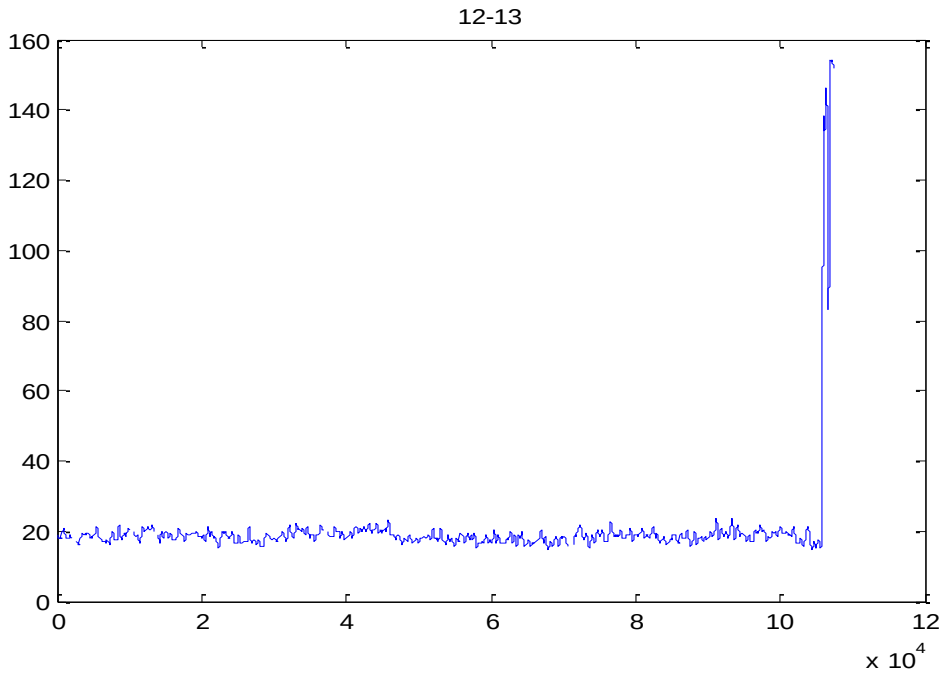

Fig2. Angle-Cross-System during 12:00-13:00

Table 10 - Results For 5 Minutes Reliability Metrics

5-Min Period	Hv1	RMSv1	Hv2	RMSv2	Ht1	RMSt1	Ht2	RMSt2	Hs	AVGs
0:00:00	0.69557	0.68198	0.63474	0.62528	0.99451	0.99363	0.98061	0.97712	0.99613	0.85265
0:05:00	0.68545	0.66532	0.62593	0.60596	0.99439	0.99418	0.97642	0.97297	0.99401	0.53501
0:10:00	0.68970	0.67549	0.62941	0.61504	0.99435	0.99404	0.97720	0.97411	0.99542	0.75252
0:15:00	0.70106	0.68236	0.63590	0.61992	0.99434	0.99404	0.97619	0.97380	0.99581	0.67730
0:20:00	0.71714	0.70336	0.64912	0.63593	0.99405	0.99396	0.97503	0.97264	0.99782	0.53801
0:25:00	0.72062	0.70604	0.65329	0.64003	0.99489	0.99409	0.97515	0.97291	0.99482	0.59214
0:30:00	0.68808	0.67670	0.63552	0.62385	0.99503	0.99480	0.97822	0.97504	0.99707	0.76179
0:35:00	0.68715	0.67866	0.63652	0.62736	0.99507	0.99464	0.97886	0.97651	0.99763	0.79774
0:40:00	0.68027	0.66786	0.63188	0.61832	0.99505	0.99484	0.97855	0.97564	0.99639	0.73533
0:45:00	0.68166	0.66602	0.62570	0.61201	0.99502	0.99479	0.97726	0.97457	0.99651	0.62025
0:50:00	0.69519	0.68042	0.63660	0.62344	0.99488	0.99446	0.97790	0.97630	0.99756	0.82366
0:55:00	0.71227	0.69295	0.65322	0.63384	0.99468	0.99449	0.97712	0.97541	1.00000	0.84580
1:00:00	0.71559	0.70309	0.65886	0.64498	0.99471	0.99417	0.97991	0.97752	0.99805	0.87438
1:05:00	0.71521	0.70526	0.65739	0.64617	0.99471	0.99448	0.97802	0.97442	0.99691	0.62707
1:10:00	0.71985	0.70809	0.66164	0.64893	0.99473	0.99461	0.97605	0.97366	0.99567	0.52385
1:15:00	0.71498	0.69806	0.65314	0.63724	0.99482	0.99456	0.97474	0.97197	0.98819	0.30890
1:20:00	0.72812	0.70512	0.66914	0.64440	0.99491	0.99461	0.97469	0.97204	0.98788	0.31784
1:25:00	0.73878	0.71736	0.68483	0.66149	0.99500	0.99480	0.97759	0.97451	0.99527	0.50186
1:30:00	0.69843	0.68104	0.64765	0.63271	0.99496	0.99475	0.97825	0.97635	0.99679	0.64974
1:35:00	0.69279	0.68170	0.64595	0.63375	0.99496	0.99485	0.97829	0.97546	0.99698	0.47255
1:40:00	0.70354	0.68840	0.65631	0.64123	0.99496	0.99445	0.98220	0.97800	0.99924	0.76250
1:45:00	0.71343	0.70016	0.66620	0.65171	0.99421	0.99376	0.98176	0.98038	0.99727	0.90511
1:50:00	0.71706	0.70441	0.66891	0.65539	0.99424	0.99339	0.98236	0.98108	0.99842	0.89378
1:55:00	0.70972	0.69721	0.66249	0.64745	0.99483	0.99438	0.98261	0.97596	1.00000	0.53454
2:00:00	0.69921	0.68163	0.64518	0.62861	0.99464	0.99318	0.97449	0.96899	0.98041	0.34641
2:05:00	0.68584	0.66990	0.63181	0.61519	0.99257	0.99133	0.96673	0.96399	0.70226	0.36848
2:10:00	0.71382	0.68748	0.65708	0.63263	0.99346	0.99223	0.96923	0.96596	0.94155	0.35592
2:15:00	0.71675	0.70035	0.65855	0.64651	0.99460	0.99392	0.97550	0.97145	0.94017	0.33604
2:20:00	0.71799	0.70329	0.65940	0.64714	0.99446	0.99365	0.97355	0.97016	0.99902	0.34869
2:25:00	0.72417	0.70873	0.66458	0.64868	0.99402	0.99330	0.97107	0.96888	0.99971	0.36836
2:30:00	0.72147	0.71038	0.66365	0.65078	0.99358	0.99286	0.96961	0.96765	0.96780	0.36497
2:35:00	0.71729	0.70470	0.66048	0.64583	0.99389	0.99259	0.97066	0.96700	0.99491	0.33143
2:40:00	0.71668	0.70353	0.66280	0.64721	0.99474	0.99423	0.97742	0.97292	0.99735	0.44074
2:45:00	0.72278	0.71119	0.66713	0.65594	0.99469	0.99448	0.97982	0.97679	0.99640	0.72942
2:50:00	0.72224	0.71056	0.66620	0.65468	0.99458	0.99438	0.97951	0.97739	0.99632	0.82759
2:55:00	0.73268	0.71376	0.68213	0.66263	0.99487	0.99365	0.98432	0.98048	1.00000	0.87213
3:00:00	0.72897	0.71823	0.67988	0.66905	0.99372	0.99203	0.98595	0.98399	0.99746	0.89209
3:05:00	0.73453	0.72391	0.68282	0.67202	0.99415	0.99305	0.98484	0.98218	0.99899	0.90872
3:10:00	0.73360	0.71959	0.68228	0.66995	0.99234	0.99074	0.98676	0.98555	0.99822	0.91310

3:15:00	0.74071	0.72547	0.69016	0.67547	0.99102	0.98960	0.98699	0.98634	0.99860	0.85307
3:20:00	0.73901	0.72915	0.69009	0.68013	0.99079	0.98918	0.98711	0.98677	0.99802	0.77690
3:25:00	0.74025	0.72822	0.68931	0.67642	0.99271	0.99118	0.98678	0.98539	0.99991	0.91973
3:30:00	0.73801	0.72587	0.68189	0.66984	0.99439	0.99352	0.98370	0.98163	0.99708	0.84969
3:35:00	0.73561	0.72413	0.67957	0.66730	0.99501	0.99415	0.98317	0.98000	0.99970	0.87058
3:40:00	0.73894	0.72542	0.68174	0.66704	0.99500	0.99485	0.97795	0.97583	0.99477	0.39696
3:45:00	0.73407	0.72282	0.67702	0.66488	0.99497	0.99483	0.97857	0.97667	0.99690	0.53696
3:50:00	0.74558	0.73200	0.68599	0.67396	0.99503	0.99485	0.97917	0.97689	0.99707	0.58690
3:55:00	0.73793	0.72730	0.68537	0.67223	0.99505	0.99480	0.98146	0.97822	1.00000	0.64443
4:00:00	0.73445	0.72199	0.67957	0.66487	0.99491	0.99467	0.98124	0.97734	0.99797	0.61555
4:05:00	0.74883	0.73155	0.69333	0.67452	0.99497	0.99471	0.98156	0.97822	0.99660	0.72182
4:10:00	0.75478	0.73767	0.69673	0.67818	0.99487	0.99469	0.98124	0.97654	0.99656	0.53302
4:15:00	0.74327	0.72449	0.68785	0.66783	0.99484	0.99442	0.98205	0.97942	0.99775	0.79292
4:20:00	0.73430	0.71973	0.67471	0.66001	0.99507	0.99474	0.97958	0.97665	0.99784	0.50240
4:25:00	0.73221	0.71153	0.66929	0.65209	0.99501	0.99454	0.97677	0.97417	0.65592	0.32650
4:30:00	0.72935	0.71535	0.67300	0.65767	0.99498	0.99476	0.98116	0.97775	0.99940	0.63859
4:35:00	0.72734	0.71216	0.67130	0.65583	0.99494	0.99475	0.98218	0.97872	0.99789	0.63780
4:40:00	0.72549	0.70608	0.66991	0.65164	0.99500	0.99450	0.98316	0.98072	0.99844	0.79159
4:45:00	0.70864	0.69766	0.65530	0.64251	0.99496	0.99459	0.98261	0.97980	0.99775	0.83055
4:50:00	0.70964	0.69632	0.65469	0.64126	0.99496	0.99474	0.98173	0.97985	0.99793	0.85360
4:55:00	0.71768	0.69957	0.66149	0.64470	0.99496	0.99458	0.98291	0.98028	1.00000	0.82342