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# Using Synchrophasor System Data for Establishing Operating Range for Operators Guidance and Detection and Analysis of Significant Events

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## SUMMARY

Under a Department of Energy (DOE) project, Electric Power Group (EPG) along with four ISOs (NYISO, MISO, PJM and ISO-NE) in Eastern Interconnection (EI), are exploring the feasibility of using synchrophasor system data [1,2] for establishing normal operating ranges for guidance to operators and identifying significant events occurring in the power system [3,4]. Establishing the normal operating ranges for angle pairs can help operators to identify if the system moves into an abnormal system state. The analysis of significant events can help to understand in detail pre and post cursors of the event. Hundreds of Phasor Measurement Units (PMU) have been installed in the EI of the United States and data is available for the analysis. The collected data has been made available to EPG by the four ISOs for the PMU's relevant to the selected angle pairs. The time-stamped data using C37.118 format was collected by each ISO independently, and combined to extract wide-area angle pair information. Even though much more information could be extracted from the provided PMU data, the project was focused on the voltage angle pairs. The objective of the project is to determine if the data can be used for (1) setting up wide-area angle pair operating ranges across ISOs, (2) wide-area system stress monitoring, (3) identifying significant system events and understanding their impacts on various regions, (4) analysis of events to understand pre and post event dynamics.

The result of the project has shown that multi-ISO PMU data can be used to determine operating ranges, and can be used by operators to identify abnormal operating conditions. ISOs can monitor wide-area stresses for regions that are not in their control area. The control chart screening technique commonly used in manufacturing for quality control could be used to filter significant events and would allow users to perform the detailed analysis on the identified events. Manufacturing industry typically uses a value of +/- 3 sigma; however, for the analysis of synchrophasor data, sigma values of 15 to 20 were found to provide good results in identifying events. Using this technique during one week period from December 1 to 7, 2014, three significant wide-area events and multiple local events were identified. Although the analysis was limited to voltage angle pairs, the analysis methodology could be applied for other parameters; such as sensitivities, oscillations or power flows to identify the abnormal system condition. In addition their trends can be combined to pinpoint degrading system conditions or near misses that may be more critical than violations of single metrics. This paper presents the analysis of the wide-area angle pairs for setting ranges and the technique used for screening large amount of data.

## KEYWORDS
Synchrophasors, power system, event analysis

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## ANGLE PAIR SELECTION

Under a DOE project, EPG along with four ISOs of the Eastern regions in the United States have been exploring the feasibility of using synchrophasor data for establishing normal operating range and for identifying/filtering significant system events in the EI power system. The objective of the project is to determine if the data can be used for:

1. Setting up wide-area angle pair operating ranges across ISOs.
2. Wide-area system stress monitoring.
3. Identifying significant system events and understanding their impacts on various regions.
4. Analysis of events to understand pre and post event dynamics.

Although the synchrophasor data can provide much more valuable information on system dynamics, the primary focus of the analysis in the present work was on use of the wide-area angle pairs only. Under the leadership of the Technical Advisory Group (TAG) which included experts from each of the participating ISOs, a list of voltage angle pairs was mutually agreed to by the ISOs for wide-area angle pair analysis. The voltage angle pairs were selected to provide good visibility of the entire system covering the four ISO regions. The TAG selected two time periods for voltage angle pair difference analysis. Furthermore, as the PMU data was captured at different sampling rates by the ISOs, the TAG group decided that the PMU data should be down sampled from 30 Hz or 60 Hz sample rate to a one Hz sample rate for the analysis. The selected angle pairs covering the four ISO regions of the EI are shown in Figure 1 below. The synchrophasor system data analyses has shows that although data was recorded at different locations, it is possible to combine the data for the purpose of analyses.

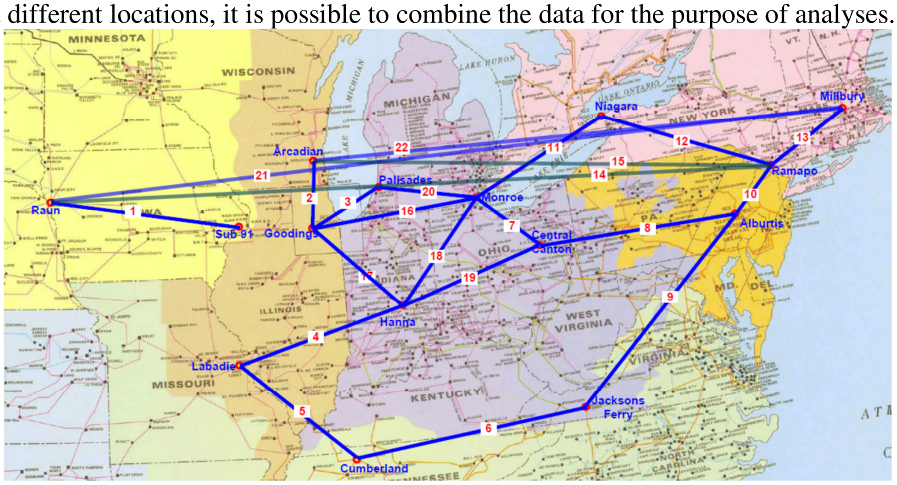

**Figure 1. Wide-area Angle pairs selected by the Technical Advisory Group.**

## DATA PREPARATION FOR ANALYSIS

Upon receipt of the data from four ISOs, data quality checks were performed. The data quality checks identified missing and error prone data which needed to be fixed before the analysis could be done. The C37.118 format includes the data quality flag which was used to classify the data errors. The Data quality reports were prepared to ensure proper synchronization. A sample data quality report for a one week period for PJM data is shown in Figure 2. A total of 604800 samples were expected to be received from each measurement point (7x24x60x60) at the one sample per second rate. Similar statistics and analysis were carried out for data from other ISOs as well.

Both voltage and current Phasor data was available, however, only the voltage Phasors were used for analysis. The data are time tagged and measurements from different locations can be compared to obtain angle pair differences. Use of current phasors can provide additional information, such as power flows, sensitivities, oscillations etc.

| Status Flag Code | 0x0000 | 0xf030 | 0xe030 | 0x2000 | 0x2010 | 0x2020 | 0x2030 | |
|---|---|---|---|---|---|---|---|---|
| Data Quality Type | Good Data | Data Invalid/ PMU Error/ Sync Error/ Sort by Arrival | Data Invalid/ PMU Error/ Sync Error | Sync Error | Sync Error/ Unlocked 10s | Sync Error/ Unlocked 100s | Sync Error/ Unlocked 1000s | Total |
| AA 05CANTNC 01 | 486300 | 118091 | 0 | 407 | 2 | 0 | 0 | 604800 |
| AA 05CANTNC 02 | 484662 | 119718 | 0 | 415 | 5 | 0 | 0 | 604800 |
| AA 05CANTNC 03 | 492564 | 111623 | 0 | 11 | 42 | 380 | 180 | 604800 |
| AA 05CANTNC 04 | 484683 | 119746 | 0 | 371 | 0 | 0 | 0 | 604800 |
| AA 05CANTNC 05 | 491992 | 112184 | 0 | 11 | 41 | 405 | 167 | 604800 |
| AA 05CANTNC 06 | 492618 | 111566 | 0 | 11 | 40 | 386 | 179 | 604800 |
| AA 05J FERR 02 | 492101 | 112699 | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 03 | 491965 | 112835 | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 04 | 497980 | 106820 | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 05 | 491996 | 112804 | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 06 | 363878 | 240922 | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 07 | 363878 | 240922 | 0 | 0 | 0 | 0 | 0 | 604800 |
| CE GOODI;2R 11 | 601228 | 966 | 2598 | 8 | 0 | 0 | 0 | 604800 |
| CE GOODI;4B 12 | 603811 | 964 | 0 | 25 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 51 | 592831 | 8479 | 3490 | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 52 | 592831 | 8479 | 3490 | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 53 | 592831 | 8479 | 3490 | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 54 | 596321 | 8479 | 0 | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 55 | 596321 | 8479 | 0 | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 56 | 596321 | 8479 | 0 | 0 | 0 | 0 | 0 | 604800 |

1. PMUs from AA have primarily have Data Invalid/ PMU Error/ Sync Error/ Sort by arrival error indicating data communication issues from AA.
2. In addition to above, PMUs from Central Canton also have Sync Error indicating clock issue.
3. PMUs from CE (Goodings) have moderate Data invalid and Sync error.
4. PMUs from PL (Alburtis) have some data invalid and additional sync error with possible communication/clock issue.

**Figure 2. Data Quality Analysis Distribution Chart for PJM System Data.**

## COMBINING DATA FROM DIFFERENT ISOs AND ESTABLISHING OPERATING RANGE

After processing the data from ISOs, the data points was combined to obtain wide-area angle pair differences. It was observed that some data required adjustments such as addition of 120 degrees or subtraction of 120 degrees to get the correct angle differences. Also, to avoid transients in the data and to get a stable operating range, the data used for analysis was modified to exclude the top and bottom 0.5 percent data. Figure 3 below shows the angle difference range, min, max and median values for these angle pairs. Analysis also showed that the data availability ranged between 72 to 96 percent and needs to be improved.

Establishing normal operating range for system operation is essential to alarm / alert operators if the system is moving from a normal to abnormal state. Statistical analysis of the data can provide the Max/Min range for the variable. Since this analysis was concentrating on validation of the data stitching and analysis technique, the analysis was conducted for two significant system loading conditions that is winter (December 14, 2013 to February 14, 2014 ) and fall ( September 1, 2014 to October 31, 2014) when extremes were expected to occur. In addition, a one week period, December 1 to 7, 2014 was also included in analysis for testing the event identification methodology.

These established ranges can be used to alarm operators if the system continues to operate outside the range or the range violation continues to increase. The range was used in analyzing post event dynamics analysis of the identified event. Statistical analysis of the data using Box-Whisker charts, Time Durations curves etc. were also performed for each angle pair.

| Index | From bus | To bus | Adjustment | % Availability | Min 0.5% | Max 0.5% | Range | Min | Max | Median | Mean | % Positive |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Raun | Sub 91 | | 94 | -10 | 25 | 35 | -13 | 27 | 10 | 9 | 79 |
| 2 | Goodings | Arcadian | Adj by +120 | 94 | -8 | 10 | 18 | -10 | 12 | -1 | -1 | 39 |
| 3 | Goodings | Palisades | | 92 | 3 | 25 | 22 | 0 | 27 | 17 | 17 | 100 |
| 4 | Labadie | Hanna | | 96 | 22 | 56 | 34 | 17 | 61 | 38 | 38 | 100 |
| 5 | Labadie | Cumberland | | 96 | -4 | 20 | 24 | -5 | 21 | 7 | 7 | 96 |
| 6 | Jacksons Ferry | Cumberland | | 78 | -52 | -26 | 26 | -54 | -20 | -40 | -39 | 0 |
| 7 | Canton Centr. | Monroe | | 77 | 3 | 29 | 26 | 0 | 31 | 14 | 15 | 100 |
| 8 | Alburtis | Canton Centr. | | 75 | -23 | 5 | 28 | -25 | 6 | -8 | -8 | 10 |
| 9 | Alburtis | Jacksons Ferry | | 76 | -33 | 11 | 44 | -38 | 14 | -14 | -14 | 6 |
| 10 | Alburtis | Ramapo | | 72 | -1 | 35 | 36 | -1 | 37 | 19 | 18 | 98 |
| 11 | Niagara | Monroe | | 74 | 1 | 51 | 50 | -2 | 55 | 29 | 28 | 100 |
| 12 | Niagara | Ramapo | | 75 | 22 | 55 | 33 | 18 | 58 | 40 | 39 | 100 |
| 13 | Ramapo | Millbury | Adj by -120 | 76 | -10 | 19 | 29 | -11 | 22 | 1 | 2 | 56 |
| 14 | Raun | Ramapo | | 73 | 33 | 128 | 95 | 25 | 138 | 96 | 89 | 100 |
| 15 | Arcadian | Ramapo | Adj by -120 | 73 | 15 | 88 | 73 | 11 | 92 | 57 | 52 | 100 |
| 16 | Goodings | Monroe | | 95 | 20 | 55 | 35 | 17 | 57 | 42 | 41 | 100 |
| 17 | Goodings | Hanna | | 95 | -3 | 29 | 32 | -4 | 31 | 11 | 12 | 96 |
| 18 | Hanna | Monroe | | 96 | 10 | 45 | 35 | 8 | 49 | 30 | 28 | 100 |
| 19 | Hanna | Canton Centr. | | 77 | -1 | 30 | 31 | -4 | 32 | 15 | 14 | 98 |
| 20 | Palisades | Monroe | | 93 | 14 | 36 | 22 | 13 | 38 | 24 | 24 | 100 |
| 21 | Raun | Millbury | Adj by -120 | 94 | 34 | 148 | 114 | 29 | 159 | 98 | 94 | 100 |
| 22 | Arcadian | Millbury | Adj by +120 | 93 | 11 | 101 | 90 | 4 | 108 | 59 | 57 | 100 |
| 23 | Raun | Orrington | Adj by -120 | 93 | 12 | 155 | 143 | 6 | 167 | 89 | 84 | 100 |
| 24 | Arcadian | Orrington | Adj by +120 | 93 | -9 | 117 | 126 | -16 | 129 | 45 | 47 | 97 |
| 25 | Ramapo | Orrington | Adj by -120 | 75 | -32 | 38 | 70 | -34 | 44 | -13 | -10 | 18 |
| 26 | Raun | Sandy Pond | Adj by -120 | 93 | 31 | 148 | 117 | 26 | 157 | 97 | 93 | 100 |
| 27 | Arcadian | Sandy Pond | Adj by +120 | 93 | 8 | 104 | 96 | 1 | 112 | 57 | 55 | 100 |
| 28 | Ramapo | Sandy Pond | Adj by -120 | 76 | -12 | 23 | 35 | -14 | 26 | -1 | 1 | 40 |

**Angle Difference Pairs involving PMUs from ISO-NE (Millbury, Orrington, Sandy Pond) were adjusted by 120 degrees**

**Figure 3. Table Showing data availability, angle pair ranges and offset correction to align data between different ISOs**.

## SIGNIFICANT EVENT DETECTION AND ANALYSIS (DECEMBER 1-7, 2014 STUDY PERIOD):

One of the major challenges with the synchrophasor system data is screening the significant events from the large amount of data that are being collected. At 30 samples per second (SPS), the data collected in a single day can amount to several giga-bytes. The analysis concentrated on development of a methodology for detection of the event, examining its impact on various angle pairs and area impacted to determine/classify the severity of the event. It was also important to see, if other system changes occurred before or after the event to identify pre-cursors or post system actions. Down sampling the data rate to one SPS reduced the data amount to be processed but still provided adequate visibility of the system dynamics. Although, angle pair analysis was used to screen the events, other parameters such as frequency, power, voltage etc., can also be used for detailed analysis of the event.

## METHODOLOGY TO IDENTIFY SIGNIFICANT EVENTS:

Under the DOE program for Smart Grid to increase visibility and the reliability of the system, several hundreds of PMUs have been installed and data is being streamed and stored. However, it is important to find out and filter the significant events that may have occurred in the system. The events can be local or global. Even the events that may be local could have global impacts and may require further analysis. In order to filter the significant events from the one week data, the Control Chart Analysis Technique, commonly used in manufacturing was used. This statistical technique is used to find the samples that are outside the tolerance band. For manufacturing processes, the tolerance band is defined as +/- 3 sigma. This tolerance band basically accepts about 99.76 percent samples and rejects only 0.24 percent samples. Since our analysis was using around six million points for one week for each angle pair and we were looking for extreme events, we selected a much higher sigma value. With a 20 sigma value, this analysis gave us about 40 events for all the angle pairs. Figure 4 below shows the detected events for different sigma values. The ISO-NE (or NE) to Ramapo angle pairs have been shown separately as they detected many more events and may have been influenced by a phase shifter.

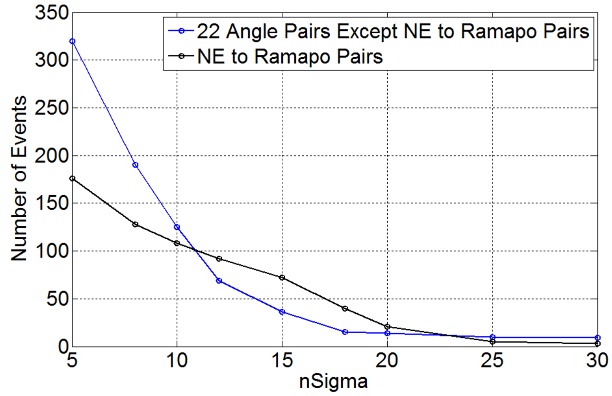


**Figure 4. Number of events detected by twenty-two angle pairs using different sigma values.**

The Control Chart Analysis technique is a three step method. The variable used for analysis was the angle pair differences for different angle pairs. To get adequate coverage of the system all twenty-two angle pairs were used for statistical analysis. The three step analysis process includes:

1. Identifying the maximum and minimum values within one-minute time window.
2. Calculating within one-minute the data change range which is equal to maximum- minimum value.
3. Comparing the one-minute change range with Upper Control Limit (UCL). The UCL is determined based on nSigma value which may be chosen between 5 and 30.

Figures 5, 6 and 7 show the process step by step for an angle pair between Raun and Sub 91. Figure 5 shows step 1 that is determining max-min value for each minute of data. Figure 6 shows plotting the max-min values for the time window and the Figure 7 shows the comparison of max-min values for an angle pair for the entire analysis period. The sigma value of 20 shows two event detected using this technique.

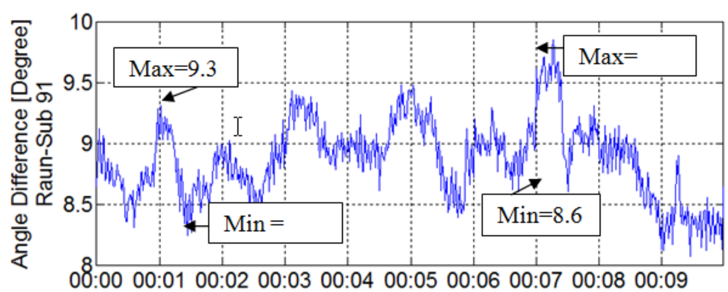


**Figure 5. Control Plot Step 1 : Find Max and Min Point in 1-Min Time Window.**

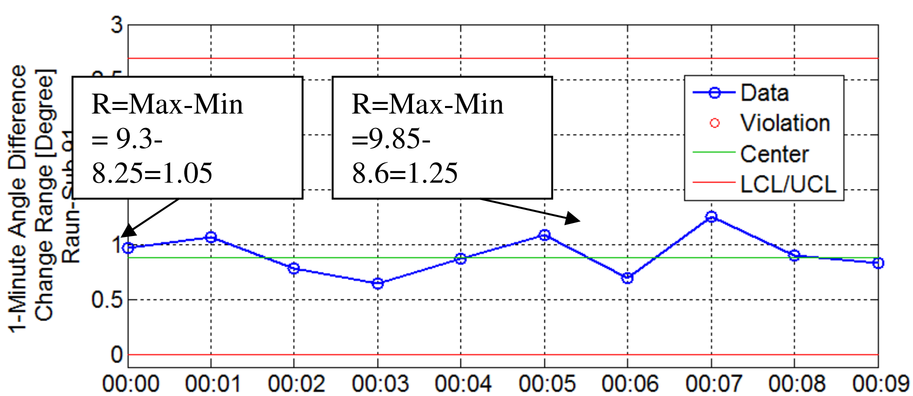


**Figure 6. Control Plot Step 2 : Calculate the Range Value for each minute.**

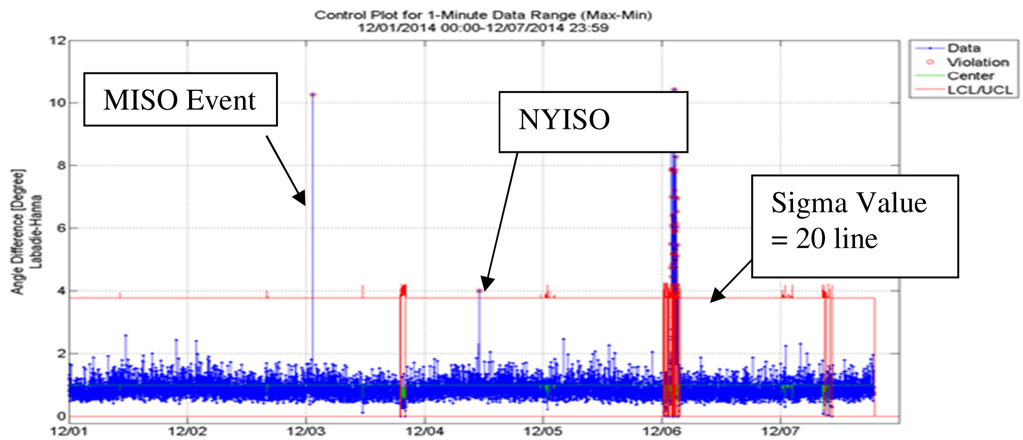


**Figure 7. Event detection using 20 sigma Upper Control Limit for Labadie-Hanna angle pair. The Hydro Quebec event 3 is not detected with sigma=20, but was detected using a sigma value of 15.**

According to the NERC report for this period, three significant events as shown in Figure 8 occurred. That is:

> ***Event 1***: Loss of 1287 MW at Callaway on December 3, 2014.
> ***Event 2***: Loss of 765 kV Messina-Marcy line in NYISO on December 4, 2014.
> ***Event 3:*** Loss of 765 kV James Bay lines and generation on December 4, 2014.

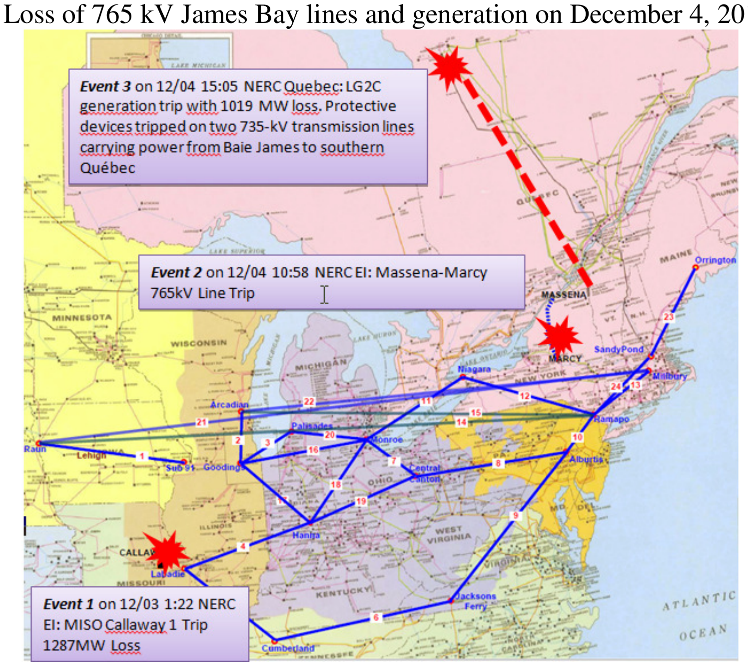


**Figure 8. Eastern Interconnection area showing locations of three events reported in the NERC report.**

Using this technique, analysis was conducted on all twenty two angle pairs. The analysis was conducted using two different sigma values to determine what sigma value will enable detection of all three events. The sigma value of 15 detected all three events. The results of the analysis are shown in Figure 9. It will be seen from the chart in Figure 9 below that the two major events were detected by multiple angle pairs. These can be classified as global events. There were several other events detected by one or two angle pairs that can be classified as local events. The global events have a wide system area impact. Interestingly, MISO or PJM may not be aware of the events in New York or Hydro-Quebec (HQ) but they would feel the impact and their systems may be stressed. Increased angle stress in PJM area could result in voltage stress on some PJM busses. The HQ event was remote from the angle pairs being used for monitoring and was not detected by other angle pairs except Sandy Pond – Orrington, which gets directly impacted as the event resulted in loss of DC power being received at Sandy Pond receiving station.

As would be seen from Figure 9, the NYISO event had the maximum impact as it impacted most angle pairs. Figure 10 shows the angle difference time plot for this NYISO event. The event shows wide-area angle increase of above 20 degrees on some angle pairs and system oscillations that damped out rapidly.

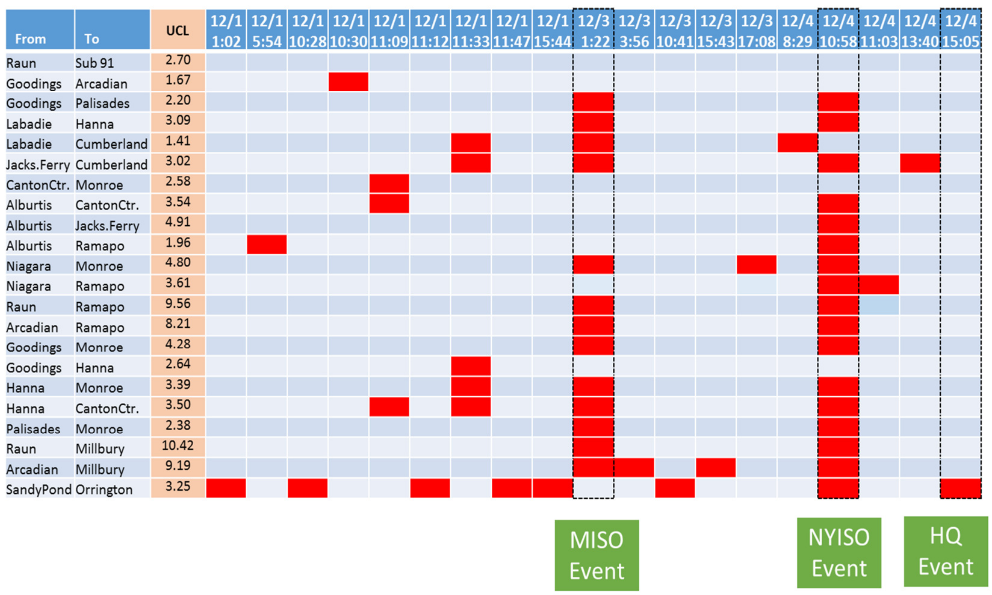


**Figure 9. Events detected by Control Charting technique using a sigma value of 15.**

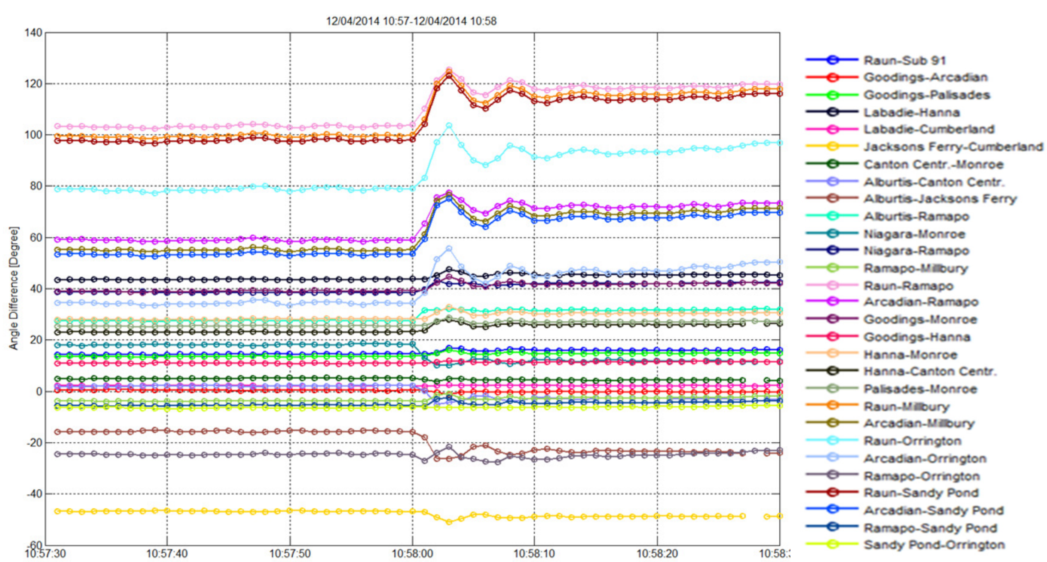


**Figure 10. Angle pair plots showing NY ISO event showing dynamic changes in the wide-area angle pairs. Several angle pairs were impacted and detected this event.**

## CONDUCTING PRE-CURSORS AND POST EVENT ANALYSIS:

One of the important aspects in system operation is that when a violation of the range or contingency occurs, the range violation or the impact of the contingency should be corrected quickly. In fact, the violation resulting from the event should get offset by an appropriate operator action. The first event resulted in reduced system stress as the generation tripped resulted in reducing the west-east power flow. The second event resulted in an increase of stress by more than 20 degrees and caused west-east oscillations. The oscillations were seen to have damped out rapidly, but the increased angle stress was seen to have persisted. The third event, however, showed continuous increase and was observed to have exceeded the operating range. Figure 11 shows tracking an angle pair and plotted over the established operating range for the Alburtis-Ramapo angle pair.

Another major advantage of synchrophasor technology is the ability to have wide area visibility. The analysis of the three events show that if this data from other control areas is available to operators and if they monitor major angle difference pairs, the operators would be able to see and analyze the event dynamics very quickly. Operators in MISO and PJM would be able to see the loss of the 765 kV line in New York and understand the voltages declining on some of their busses and operators in PJM, MISO and New York would be able to see increasing stress on their systems resulting from HQ event.

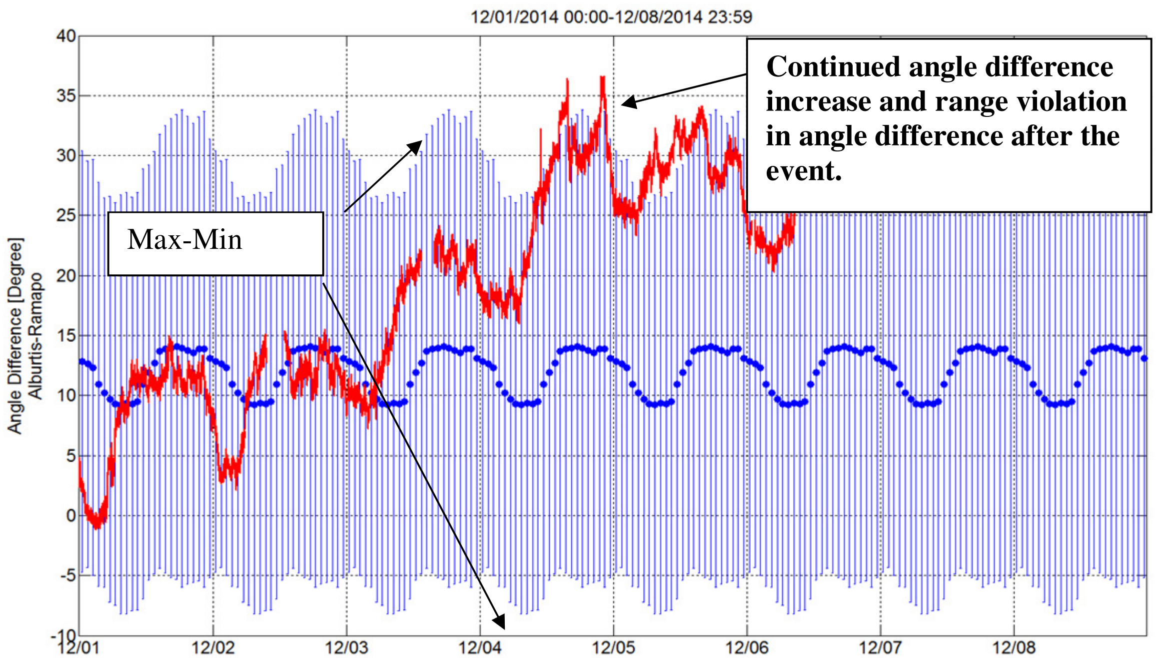


**Figure 11. Tracking angle pair differences to analyze pre- and post-event analysis.**

The pre and post cursor analysis of three events showed that in first two events, the events did not result in continued violation, however in the third event violation continued to occur. Figure 11 shows the Alburtis-Ramapo angle difference plotted over the operating range for a few days after the event. The pre/post cursor analysis of this event indicated that the event resulted from loss of generation in HQ and the angle difference could not be brought within the range as power to Sandy Pond could not be restored and, on the contrary, power had to be fed to HQ to compensate the generation loss. The angle difference is also seen to exceed the operating range.

## CONCLUSIONS:

Enormous amount of data are being collected by synchro-phasor systems installed in different regions of United States and other countries. Most of the data are collected by control areas locally. For wide-area visualization and analysis of the significant events, the data have to be shared, exchanged or combined. In order to process the data and to extract information of the significant events, and to analyze their impacts, the data have to be reviewed, combined, phase adjusted and analyzed. For the angle pair analysis, the data were down sampled from 30 SPS to one SPS and were found to be adequate. Wide-Area angle pair information is required to conduct this type of analysis and is feasible with time-tagged synchro-phasor system data. The analysis of the data from four ISOs has shown that the data can be combined even though recorded by different organizations at different locations. Pre-cursor and post event analysis can also provide information of the events as they develop, which could be very useful to operators for improving the system performance. The analysis technique used for event detection successfully detected three events and can be used for detection and analysis of the events.


## ACKNOWLEDGEMENTS:

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