BASELINING STUDY WITH A FOCUS ON EASTERN INTERCONNECTION
Subcontract 6996016

Interim Report

For Event Precursor Study

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DISCLAIMER

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PREFACE

Electric Power Group (EPG) has been working on baselining analysis for Eastern Interconnection and the project has been extended to research and study event precursors which could be used by operators in improving the system performance. This is the interim report focusing on the event precursor study.

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1. EXECUTIVE SUMMARY

Synchrophasor technology enables control center operators to monitor power grid dynamics in real-time over a wide-area of an interconnection or the entire interconnection. To make use of synchro-phasor technology and to prevent blackouts, operators need information on normal and abnormal grid performance patterns for a range of key system parameters such as system stress (angle differences), low damped or growing inter-area oscillations, voltage degradation, voltage and angle sensitivities and other parameters so that the operators are alerted to take appropriate mitigating actions. Programs are now available to monitor these dynamic power system metrics in real-time. The Eastern Interconnection Baselining study was initiated to distinguish normal and abnormal parameter ranges that can be expected in real-time operations. The objective of this study is to analyze grid metrics and baseline performance for a range of metrics including:

- Wide Area angle pairs (Inter-ISOs for wide-area stress).
- Inter-area power flows and oscillations (major inter-area power transfers).
- Voltages on sensitive/critical busses.
- Voltage and angle sensitivities at critical busses.

These baselining analysis results can provide guidance to operators on:

- normal operating range
- abnormal operating range
- pattern of metrics
- establish ranges for alarms that warrant operator's action.

Electric Power Group (EPG) was asked to work with the leadership of the Operations Implementation Task Team (OITT) and the Planning Implementation Task Team (PITT) of North American Synchro-Phasor Initiative (NASPI), as well as independent system operators (ISOs), regional transmission owners (RTOs), and utilities to carry-out interconnection baselining analysis. The PITT and OITT teams identified baselining phase angles as their highest priority. Although, the analysis can be conducted for all four metrics quantities, this present work has been limited to "Wide Area Angle Pair Analysis". The goal of this Eastern Interconnection Baselining Analysis Project is to work with the NASPI Operations and Planning teams and other Consortium for Electric Reliability Technology Solutions (CERTS) research performers, such as Pacific Northwest National Laboratory (PNNL), to carry out a comprehensive baselining analysis for establishing the high/low ranges for selected angle pairs. The study covered four ISO regions in Eastern Interconnection, NYISO, PJM, MISO and ISO New England.

As a first step in the analysis process, only the five minute State Estimator (SE) data was used for analysis. The State Estimator data from different ISOs ranged from a few months to about two years (2010-2011). Twenty-two (22) angle pairs were selected based on either input from the ISOs or by analyzing different sources and sinks in the region. Detailed statistical analysis was conducted on the data extracted from the SE data, and a recommended range was provided for each of the angle pairs. Box-whisker plot and time duration curve were introduced to set the operational monitoring range. The methodology was applied to all four individual ISOs. For Inter-ISO study, SE data from different ISOs was "stitched" or combined and time-aligned to obtain ranges for wide-area (Inter-ISO) angle pairs. It was soon realized that this approach was not feasible with SE data and instead synchronized phasor data is required. The analysis results using State Estimation data can be found in the 2014 "BASELINING STUDY WITH A FOCUS ON EASTERN INTERCONNECTION" report submitted on August 6, 2014 **[1]**.

The analysis methodology developed with state estimation data has been extended and applied to synchrophasor data. The Synchro-phasor system data is time-stamped and data from different regions can be combined, however, the data quality needs to be improved. The methodology that had been developed for SE data analysis was applied to two periods of two months of synchro-phasor data. The data for two months each from December 15, 2013 to February 14, 2014, and from September 1, 2014 to October 31, 2014, representing the winter and fall periods respectively were used with one second data samples. The Data quality was checked, clustering analysis conducted for both seasons, and initial oscillation study was performed. In addition to baselining of angle pairs, the ISO Technical Advisor Group (TAG) members requested an analysis of the correlation between the angle pair differences and the Locational Marginal Price (LMP). Overall, initial analysis shows no strong correlation between LMP and angle difference. Based on ISO TAG members' request, the angle pair difference behavior during abnormal conditions was also studied. Event detection and analysis was performed using the control chart analysis on the one week data during Dec 1-Dec 7 2014. The analysis technique successfully detected events for one week of December 2014 which can be found in the 2015 "BASELINING STUDY WITH A FOCUS ON EASTERN INTERCONNECTION" report submitted on August 24, 2015 **[2]**.

When an event occurs resulting in normal operating range violation, it should be corrected promptly by an operator action. Lack of operator action to correct such violations in past has resulted in event escalation resulting in blackouts. Analysis of pre or post cursors such as threshold violations, trends and rate of change can be important performance indicators in avoiding such escalations. Baselining analysis has been extended to research and study event precursors which could be used by operators in improving the system performance. Although, the event precursor can be a range of metrics including wide-area voltage angle, system loading, oscillation or high sensitivities, this initial study is limited to the voltage angle pair difference only. With the current available data, several signatures of angle pair difference (value, rate of change, trend and pattern) which can serve as event precursors have been studied. Some key findings of the precursors study are listed below:

- Precursor is not likely to be found before trigger/initial events.
- Line and generator trips and single contingencies may have no early warning sign but impact wide-area system stress.
- Precursors do exist during cascading events and can provide early warning to operators.
- Event precursor research is promising – needs more data for analysis to understand precursor patterns and thresholds for use in operations.

2. BACKGROUND

Major blackouts that have occurred in the last twenty years worldwide have identified the need for real-time wide-area monitoring of power system dynamics using phasor system technology.

With the advancement in the phasor system technology, it is now possible to identify the system stress and other issues, such as growing inter-area oscillations or voltage degradation early enough so that the operators are alerted to take appropriate action and avoid cascading events. Real-time tools are available to monitor these dynamic metrics. However, operators need guidance on the normal and abnormal system conditions that can be expected in real-time operations, as well as to define thresholds to alert the operators when the system is moving from a secure state to a less secure state warranting action. Some of the metrics that can be monitored using the high-speed and high-resolution time-stamped phasor system data are:

- Wide Area angle pairs (Inter-ISOs for wide-area stress).
- Inter-area power flows and oscillations (major inter-area power transfers).
- Voltages on sensitive/critical busses.
- Voltage and angle sensitivities at critical busses.

The Department of Energy, via Lawrence Berkeley National Laboratory (LBNL), commissioned Electric Power Group, LLC (EPG) to work on the Eastern Interconnection Baselining Study under subcontract 6996016. EPG is a member of the Consortium for Electric Reliability Technology Solutions (CERTS). EPG was asked to work with the leadership of NASPI's Operations Implementation Task Team (OITT) and the Planning Implementation Task Team (PITT), as well as independent system operators (ISOs), regional transmission owners (RTOs), and utilities to carry-out interconnection baselining. The PITT and OITT teams of North American Synchro Phasor Initiative (NASPI) identified baselining of Eastern Interconnection phase angles as their highest priority.

The goal of this Eastern Interconnection Baselining Analysis Project is to work with the PITT and other CERTS research performers, such as Pacific Northwest National Laboratory (PNNL), to carry out a comprehensive baselining analysis study. This analysis focuses on presenting statistical measures of phase angle range for the Eastern Interconnection covering the footprints of four Independent System Operators (ISOs) in the Eastern region. The four ISOs currently being analyzed are PJM Interconnection, Midwest ISO, New York ISO, and ISO New England. Prior work which has been performed by using 5-minute state estimator was summarized in 2014 technique report submitted on August 6, 2014 **[1]**. With synchrophasor data becoming available, the State Estimator results can be used as a starting point. The information and methodology developed in an earlier study has been exercised to build a historic view for four ISOs by using synchro-phase data. The complete detail can be found in the 2015 "BASELINING STUDY WITH A FOCUS ON EASTERN INTERCONNECTION" report submitted on August 24, 2015 **[2]**.

When an event occurs and results in range violation, it should be corrected promptly by an operator action. Lack of operator action to correct such violations in the past has resulted in event escalation resulting in blackouts. Baselining analysis study should be extended to a research and study event precursors which could be used by operators in improving the system performance. Analysis of precursor or post event system behavior such as threshold violations, trends and rate of change can be important performance indicators in avoiding such escalations. Although, the event precursor can be a range of metrics including wide-area voltage angle, loading, oscillation or sensitivity, this initial study is limited to the voltage angle pair differences.

With the current available data, several signatures of angle pair differences (value, rate of change, trend and pattern) which can serve as event precursors have been studied.

3. RESEARCH CASCADING EVENT PRECURSORS

3.1 Three Major Blackouts in North America Review

There have been a number of major blackouts in North America. An analysis of three major blackouts shows that typical blackouts start with initial disturbances or trigger events followed by a sequence of cascading events. The causes of the initial event are usually complex. A single event (line or generator trip) may have no early warning sign and a precursor is not likely to be found before trigger/initial events, but can result in stressing the system and push it into a vulnerable state.

WECC Blackout, August 10, 1996 Review [3]

Figure 1 provides the timeline for the WECC 1996 blackout. The WECC blackout event started with the Big Eddy-Ostrander line flashed and grounded to a tree without any indicator or precursor, followed by multiple transmission line outages during a period of about one and half hour weakening the system, leading to voltage decay and oscillations and then pushing the system into blackout. The decreasing damping and growing oscillations on Malin-Round Mountain lines could have served as blackout risk precursor and provide at least 10-minutes lead time.

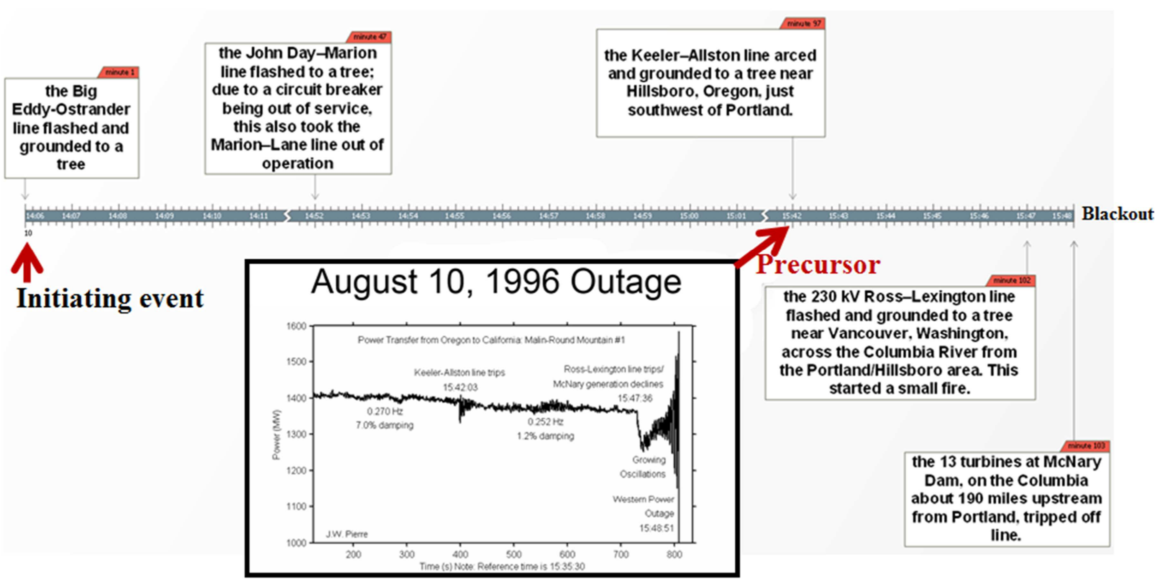

Figure 1: **WECC Interconnection-August 10th, 1996 Blackout Timeline**

Northeast Blackout, August 14, 2003 Review [4]

Figure 2 provides the timeline for the northeast blackout. This blackout's primary cause was a software bug in the alarm system at a control room of the FirstEnergy Corporation, located in Ohio. A lack of alarm left operators unaware of the need to re-distribute power after overloaded transmission lines hit unpruned foliage, which triggered a rare condition in the control software. What would have been a manageable local blackout cascaded into massive widespread distress on the electric grid. The event took three hours from initial event to blackout. The increasing angle differences between Cleveland and West Michigan, suggests that large angle differences precursor could have alerted the operators of the blackout risk with at least one hour of lead time.

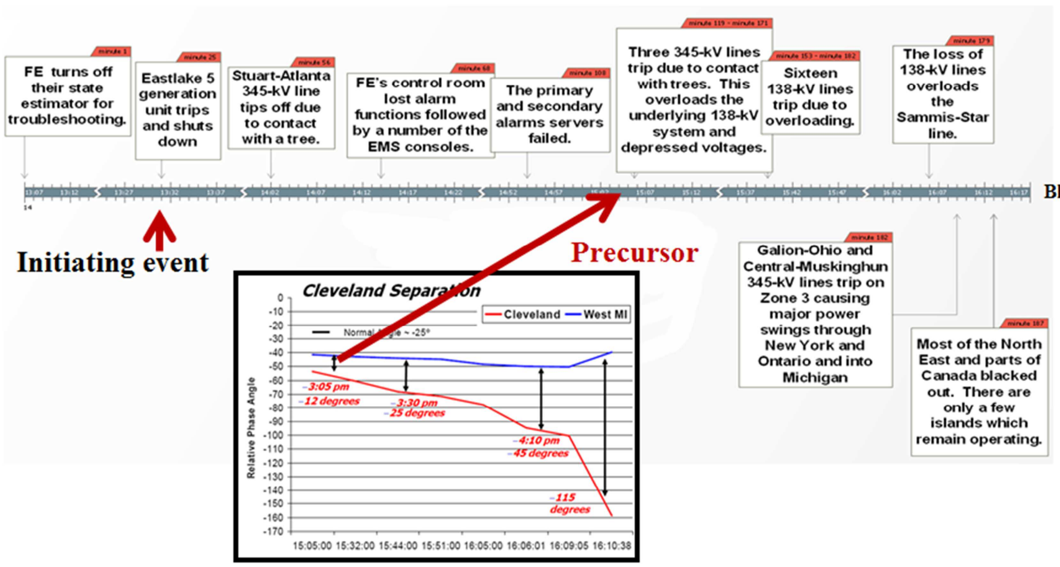

Figure 2: **Eastern Interconnection-August 14th, 2003 Blackout Timeline**

Pacific Southwest Area System Blackout in 2011 Review [5] [6]

Figure 3 shows the timeline for 2011 pacific southwest area blackout. The 2011 pacific southwest area blackout initiated by the loss of a single 500 kV transmission line. The flow redistribution of power flows created sizeable voltage deviations and equipment overloads had a ripple effect, eventually resulted in the complete blackout in absence of operators' corrective action. Just seconds before the blackout, Path 44 carried all flows into the San Diego area as well as parts of Arizona and Mexico. The excessive loading on Path 44 initiated an intertie separation scheme at San Onofre Nuclear Generating Station (SONGS). The increasing loading on Path 44 and angle difference of selected angle pairs could have served as precursor to blackout risk which kept increasing during the 11-minutes of the event.

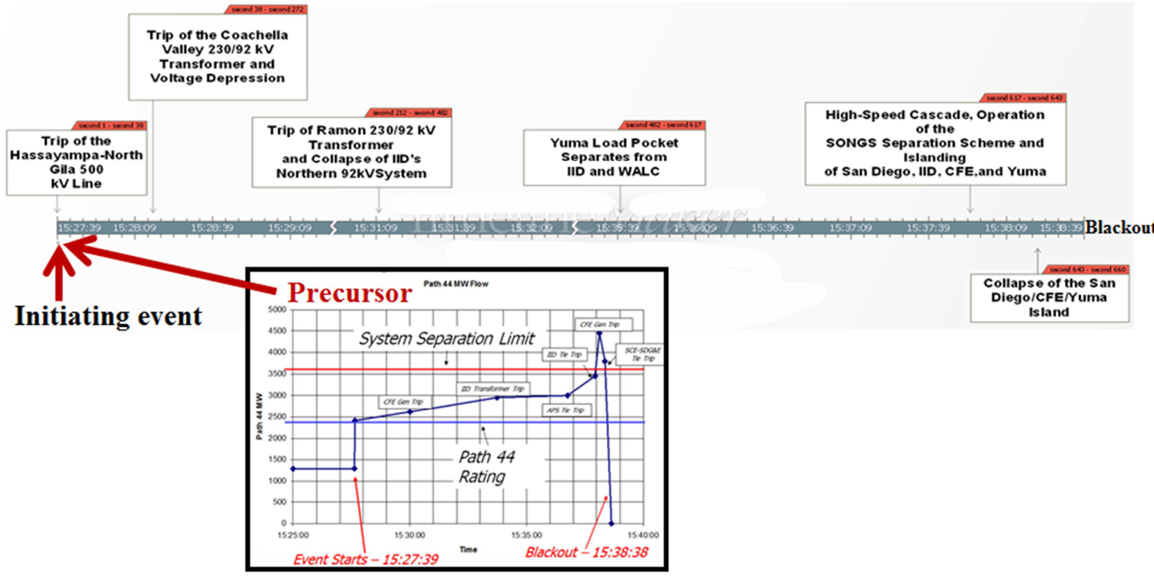

Figure 3: **Pacific Southwest Area System 2011 Blackout Timeline**

Findings

The analysis of three major blackouts shows that all three major blackouts occurred with initial disturbance or event trigger followed by a sequence of cascading events. The causes of initial event are usually complex. It can be a fault, equipment failures or malfunctions, communication and information related problem, mis-operation of protection equipment and/or human error. It also can be some external factors such as tree contact, lightning and excessive line sagging in summer. Single event (line or generator trip) may have no early warning sign and precursor is not likely to be found before trigger/initial events, but can result in stressing the system and push it into a vulnerable state. Therefore, during the cascading events precursors would exist and can provide early warning to operators.

3.2 Candidate cascading event precursors metrics

Although, the event precursor can be a range of metrics including wide-area voltage angle, loading, oscillation or sensitivities, this initial study is limited to the voltage angle pair difference. The key signatures of angle pair difference data have been studied as cascading event precursors including their value, rate of change, trend and pattern etc.

Value of Phase Angle Difference

The 2003 Northeast blackout suggests that large angle differences could be a precursor to significant events. If an operating normal reference range is established, an early alarm could be sent out before the system starts cascading. The baselining studies **[1] [2]** have developed methodology to produce angle limits that define normal operating range. The technique has been further improved and refined to have unbiased reference range compared to the technique described in 2015 technique report **[2]**.

Figure 4 is an example for angle pair difference between Hanna-Monroe with the operating reference range for the first two weeks of January 2014. In order to have unbiased reference range, only 0.1%-99.9% percentiles of two months of winter data from Dec 15 2013-Feburary 15 2014 is used. The blue reference range which is shown in the plot gives 99.9% prediction hourly interval based on 2-month of unbiased history data. The operating reference range varies based on the hour of the day and whether the day is weekday or weekend. The blue dot in the figure is the hourly mean value of the 2-month of unbiased history data which indicates the pattern of the angle pair difference throughout the day

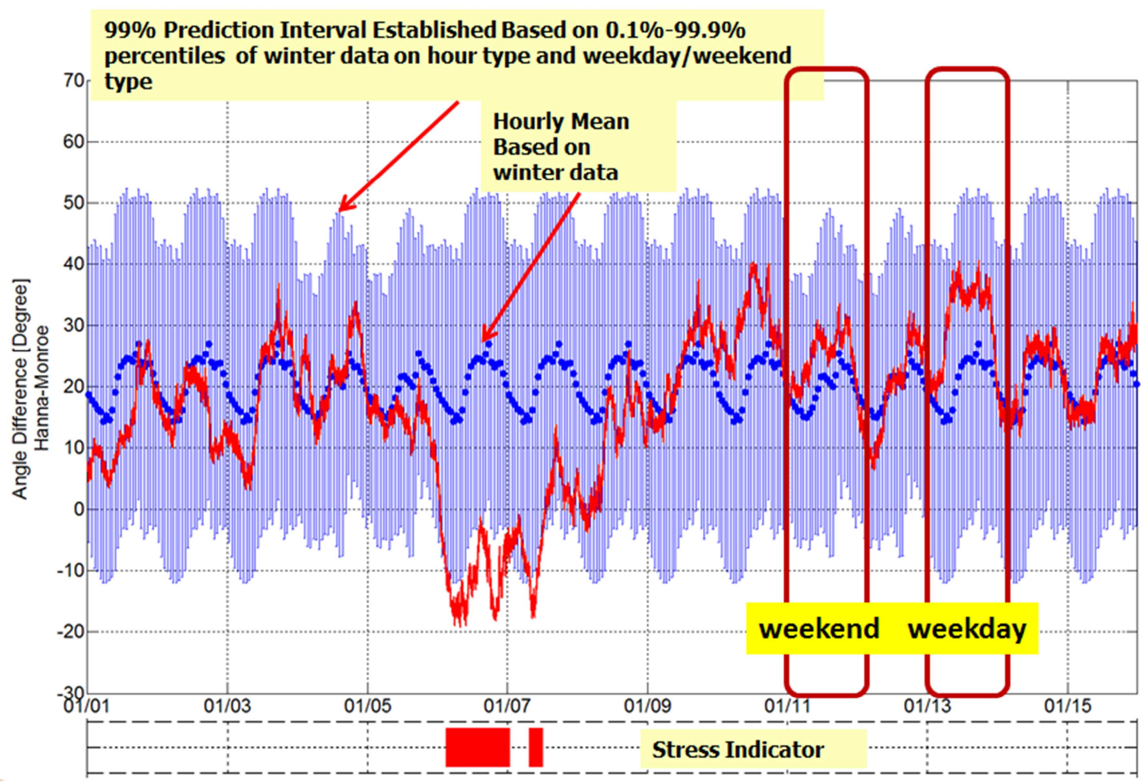

Figure 4: **Precursor Study: Precursor Developed when Angle Difference Exceeds Reference**

The red line in the figure is the actual angle pair difference value for angle pair Hanna-Monroe from January 1- January 15 2014. It is found that the angle pair started to drift from its normal range at the beginning of January 6 and then outside of the reference range in the mid of January 6, till the end of January 7. It went back to its normal operating range thereafter. This indicates that the system was in abnormal condition during that period. The situation is confirmed with North American Electric Reliability Corporation (NERC) event report **[7]** which indicates that an extreme cold weather condition occurred in lower latitudes than normal, resulting in temperatures 20 to 30° F below average. Some areas faced days that were 35° F or more below their average temperatures. These temperatures resulted in record high electrical demand for these areas on January 6 and again on January 7, 2014. The example demonstrates, with the angle pair difference reference range established, the system abnormal condition can be easily identified and some necessary precautionary steps may be followed.

Rate of Change of Phase Angle Difference

Rate of change in phase angle difference can also serve as event precursor. Previous baselining study **[2]** developed control-chart technique to detect system disturbance by focusing on rate of change of angle pair difference. Control charts **[8]** are generally used in a production or manufacturing environment and used to control, monitor and improve a process. A control chart is a graph or chart with limit lines, called Upper/Lower control lines. With the established control limit lines, the operator will immediately see that the point is exceeding one of the control limits. Further, the operator would need to investigate the cause and take proper action to correct the situation.

The limit lines in the control chart are called control lines. There are basically three kinds of control lines: the upper control limit (UCL), the central line and the lower control limit (LCL). The UCL and LCL are usually calculated based on default value 3 which represents 3σ. For normal distribution, 99.7% of data is within 3 times of standard deviation. To find the extreme system events, 20 sigma tolerance bands are used in previous baselining study **[2]**.

A study to find an appropriate sigma value is performed. Figure 5 provides the number of events as a function of sigma value used for analysis. The figure shows that lower level of nSigma will capture too many events while higher level of nSigma will miss some events. Tests were performed on one week of December 2014 data which had three NERC events. With 15 sigma, there are total 36 events can be detected. All three NERC significant events are detected. With 20 nSigma, there are total 14 events that were detected. Two NERC significant events are detected with one event missed. This event was fairly remote from the area being monitored. It is suggested that a value of 20 nSigma can be used to identify extreme system events.

Figure 6 summarizes all the identified events detected by all selected angle pairs with nSigma = 20. Top of the table provides the date/time of the detected events and the left two columns list all selected angle pairs. The cells with red color indicate there is an event detected by a specific angle pair. Two known NERC major events are detected by seven or more selected angle pairs, and twelve local events are found by three or less selected angle pairs.

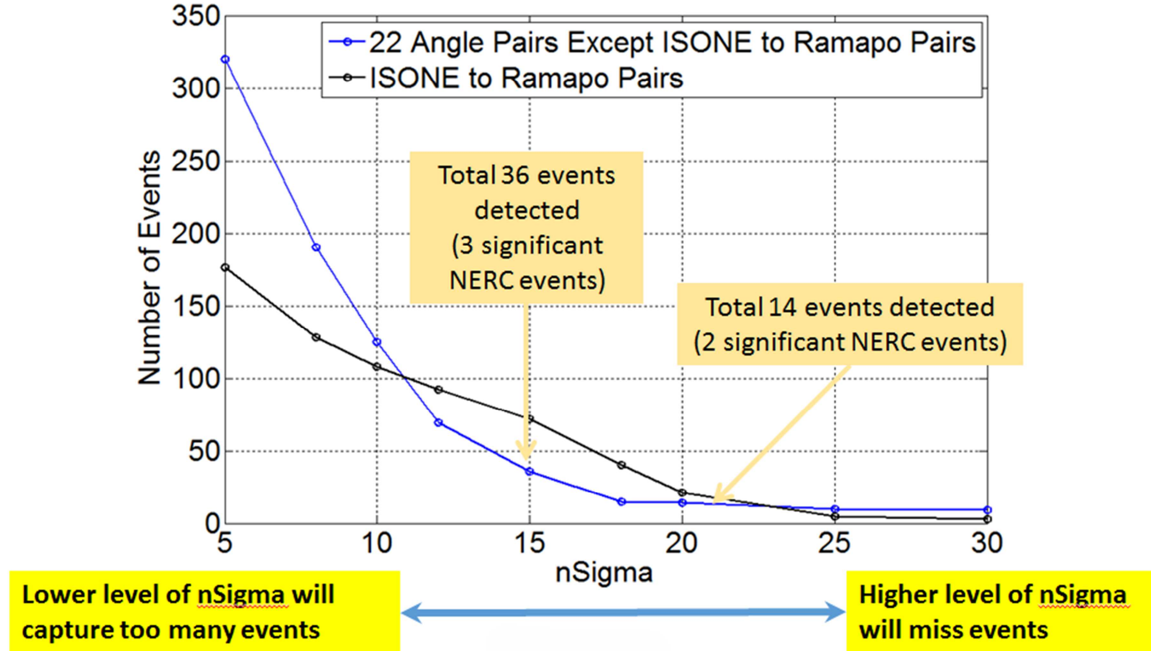

Figure 5: **Number of Events as a Function of Sigma Value Used for Analysis**

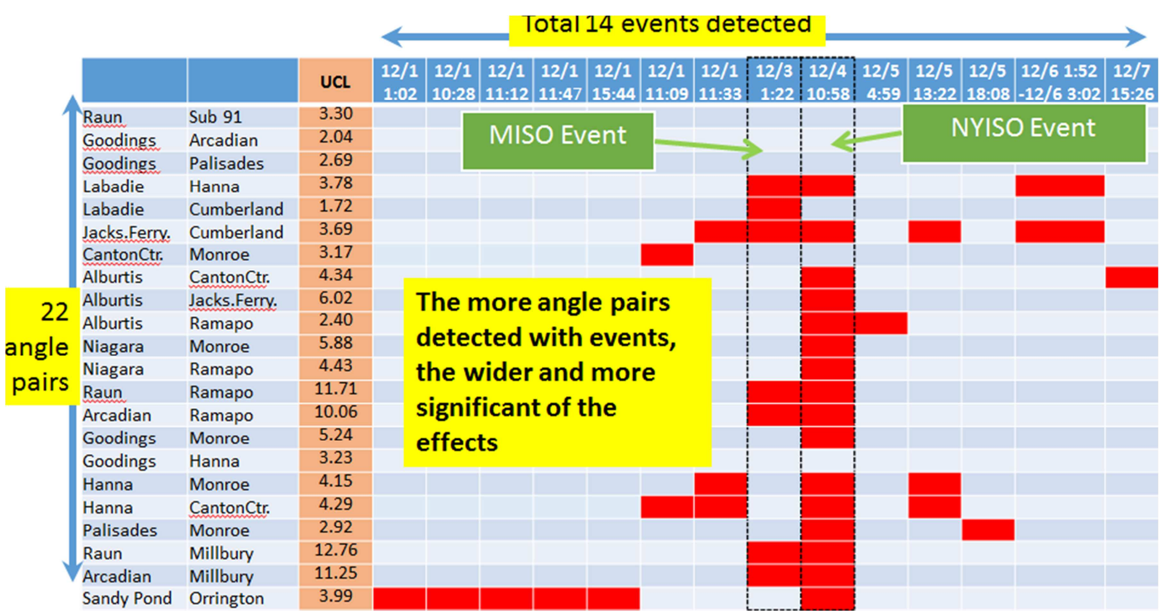

Figure 6: **Detected Events Summary (nSigma=20) for 12/1/2014-12/07/2014**

The statistical control chart analysis technique which focuses on rate of change of phase angle difference has demonstrated the capability to screen the large amount of data and detect the significant events. This technique can enable the operator to identify the significant system disturbances **[9]**.

Trend of Phase Angle Difference (Pattern Change)

Trend identification and pattern recognition technique can also provide valuable operational information and serve as event pre-cursors which may indicate system vulnerability. Many electrical appliances show a recurring pattern of power consumption throughout their operational phases. Pattern exists in power systems and pattern recognition is being widely used. If any observations do not conform to an expected pattern, it may indicate the system anomaly or vulnerability. Figure 4 shows an example for angle pair difference between Hanna-Monroe for the first two weeks of the January 2014. The blue dot in the figure shows the angle pair difference value pattern throughout the day, which is the hourly mean value of the 2-month of unbiased history data. On January 6, the angle pair difference started to show decreasing trend which does not conform to the blue dotted daily pattern line. It is a system vulnerability signal which emerged much earlier than the time when the value exceeded the reference range. This initial study using trend identification combined with pattern recognition technique is promising in angle pair difference precursor study. More study work is needed to understand precursor trend/pattern for use in operations.

The signatures of angle pair difference which can be used as precursor are value, trend and pattern. Next, some detailed analysis is performed to understand these system vulnerability precursors used in real cases.

3.3 Detailed Case Study

Case 1: 12/23/2013 11:06:58 PM, TVA Cumberland Trip Event

On 12/23/2013 11:06:58 PM, TVA Cumberland #1 generator tripped with 474 MW loss. Figure 7 shows the angle pair difference behavior during the studied event case. By using rate of change control chart technique, system disturbance can be detected by angle pair (Jackson Ferry-Cumberland). The operator should be alarmed that something happened in the system. After the event, the angle pair exhibits increasing trend and then exceeds the reference operating range. It can forewarn the operator that an event has occurred and abnormal condition is experienced by the Jackson Ferry-Cumberland angle pair.

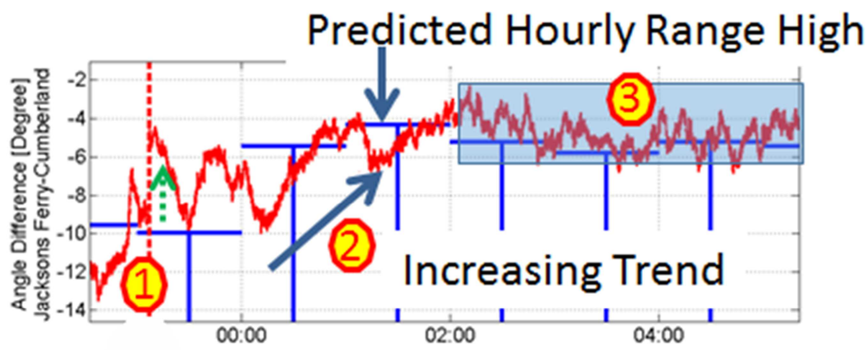

Figure 7: Jackson Ferry –Cumberland Angle Pair Difference Behavior during Case 1 Event

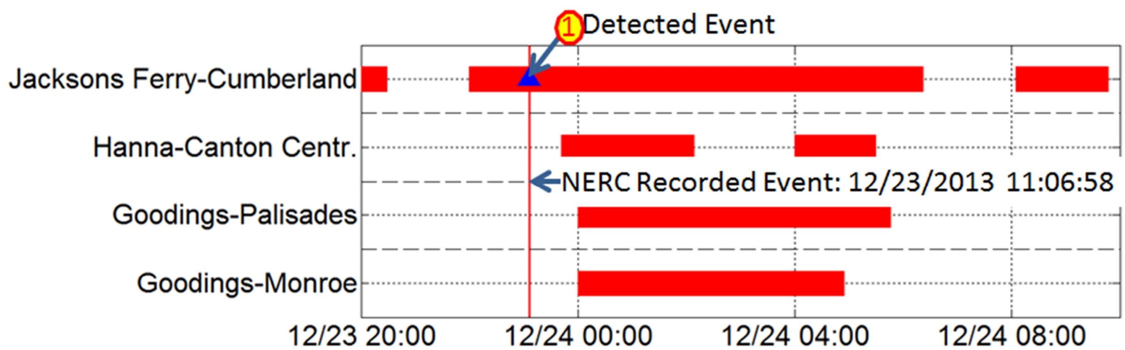

Figure 8: Selected Angle Pair Difference Behavior during Case 1 Event

Figure 8 shows four angle pair difference behavior during the studied event case. Blue triangle symbol (Δ) in the figure means there is system disturbance detected by angle pair Jacksons Ferry-Cumberland by using rate of change control chart technique. The red bar indicates date/time when angle pair exceeds the predicted angle pair reference range. There are total four angle pairs experiencing abnormal system condition before or after the event. This example shows how the reference range violations, trends and rate of change can be used as performance indicators in order to avoid any system event escalation.

Case 2: 9/6/2014 9:30:47 AM, Amos 2 Unit Tripped Event

On 9/6/2014 9:30:47 AM, Amos 2 unit tripped with 674 MW Loss. The system event can be detected by two angle pairs, Labadie-Hanna and Labadie-Cumberland, which is indicated with triangle symbol (1) (Δ). After the system event, several angle pairs show increasing/decreasing trend (2) and then the value of angle pairs are outside the prediction range (3) which is indicated with red bar.

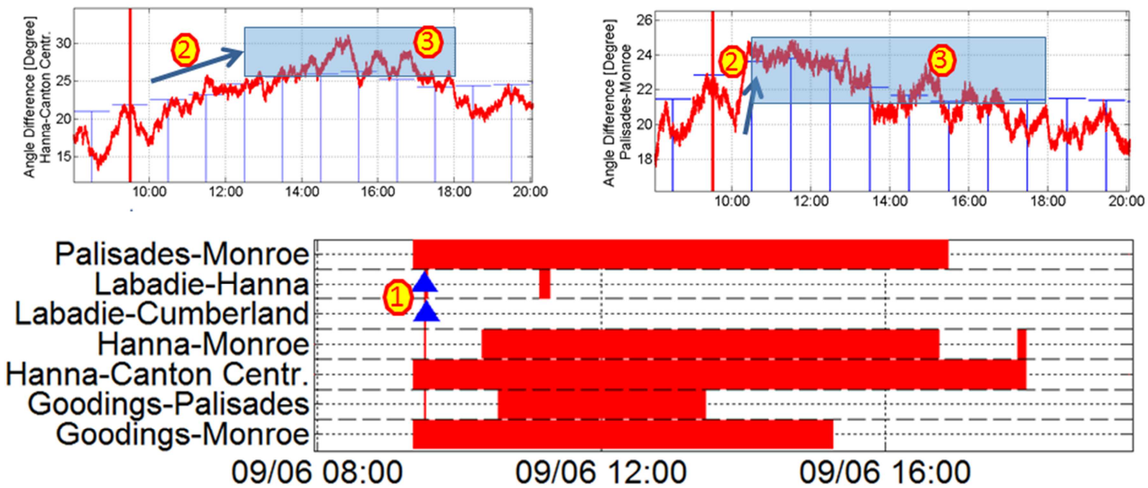

Figure 9: Selected Angle Pair Difference Behavior during Case 2 Event

Precursor Study for September-October 2014 Event Summary

More detailed analysis is performed to all of the significant events found from September to October 2014. The significant events are collected from NERC RS monthly Candidate Frequency Events **[10]** report. Table 1 below lists date/time of the recorded events during September and October 2014, the name of the tripped unit and the total MW loss. The table indicates whether the event can be detected by rate of change control chart technique or not. If it can be detected, Yes will be indicated in the cell of table together with the number of nSigma used for detection shown in the parentheses. The table also provides if there is trend observed or value violations. If there is no value violation or trend observation, the cell of the table is left empty. In summary, out of 41 significant events recorded, 16 events can be detected by rate of change control chart technique by one or more angle pairs, and 14 events have angle pair value violation of trend observation as vulnerability precursors.

Date/time	MW	Unit	Detected?	Angle Precursor Matrices
09/06/2014 9:30:47	674	Amos	Yes(20)	Value/Trend
09/14/2014 0:25:22	427	OG&E's Sooner		
09/14/2014 15:37:29	770	Dolet Hills		
09/18/2014 6:00:14	NA		Yes(15)	Value/Trend
09/19/2014 20:23:55	429	GRDA	Yes(15)	Value/Trend
09/20/2014 19:41:11	1251	Amos	Yes(20)	Trend
09/21/2014 6:11:55	NA			
09/26/2014 8:45:04	779	North Longview		
09/26/2014 9:35:13	685	KCPL's Iatan		
09/27/2014 11:38:45	465	AEP's Northeast #2		
09/29/2014 11:04:05	NA		Yes(15)	
10/01/2014 9:15:09	NA			
10/04/2014 4:19:16	753	Amos		
10/04/2014 19:28:28	NA			
10/05/2014 7:05:53	NA		Yes(20)	
10/07/2014 16:11:54	NA		Yes(20)	Trend
10/08/2014 6:28:47	NA			Trend
10/09/2014 9:30:05	848	PN CONM 2	Yes(20)	

10/11/2014 16:57:13	810	AMIL Prairie State-1	Yes(20)	
10/13/2014 7:57:53	906	Surry 2	Yes(15)	Trend
10/13/2014 15:11:26	627	Harris 2	Yes(15)	
10/13/2014 16:48:05	NA			Trend
10/14/2014 4:41:15	764			
10/15/2014 2:53:13	789	Zimmer		
10/16/2014 13:32:40	590	Westar's Jeffrey #3 tripped	Yes(20)	Trend
10/17/2014 4:03:22	NA			Trend
10/17/2014 14:31:15	NA			
10/18/2014 2:48:44	739	Zimmer 2		
10/18/2014 6:59:44	NA			
10/18/2014 9:44:06	NA			
10/20/2014 2:18:39	1320	Perry unit tripped	Yes(20)	
10/20/2014 16:41:10	NA		Yes(20)	
10/22/2014 2:31:23	454	New Madrid #1	Yes(15)	Trend
10/22/2014 13:08:20	311	Williams Generator		
10/23/2014 7:00:04	756	Kammer 2	Yes(15)	
10/23/2014 16:41:53	602			
10/24/2014 18:43:23	861	Prairie State Unit 2	Yes(20)	
10/26/2014 11:31:10	NA		Yes(20)	
10/27/2014 2:29:25	502	Muskogee #5		Value
10/27/2014 4:59:47	NA		Yes(20)	Value
10/30/2014 5:39:20	NA			Trend

Table 1: **September-October 2014 Precursor Study Summary**

3.4 Summary

Precursors are early indicators of potential events that could be mitigated by timely action. Many major blackouts, e.g., WECC 1996, EI 2003, and others had identifiable event precursors. However, it should be noted that precursors cannot foretell or forewarn about initial events. Line trip/generator trips may have no early warning sign, but impact wide-area system stress which may be precursors to subsequent events. When an event occurs, it will result in range violation, rate of change, trend observation/pattern nonconformity. Precursors point to vulnerability after initial event and before subsequent cascading events. Threshold violations, trend/pattern and rate of change are very important performance indicators in detecting and avoiding escalations. More analysis and research is required to advance the understanding of event precursors – which metrics, combination of metrics, and metric values to evaluate best approach for use of precursors in real-time operations.

4. SUMMARY OF KEY CONCLUSTION AND FINDINGS

- Precursor unlikely to provide warnings about trigger/initial events such as line trips and generator trips.
- Initial events can provide measurements – rate of change, value changes, etc. that could in combination provide precursors for future events.
- Cascading event precursors do exist and can provide early warning to operators.
- Event precursor research is promising – needs more analysis to understand precursor patterns and thresholds for use in operations.

5. AREAS FOR FURTHER RESEARCH AND DEVELOPMENT

The Eastern Interconnection Baselining study has shown that phasor data can be used effectively for baselining performance - ranges and operating thresholds. The established ranges/threshold can be used to alert operators if system is subjected to abnormal loading situation. The technique developed in the research has been demonstrated successfully in angle pair operating range identification and event detection. The current major research can be extended into several areas for further research and development as described below:

1. Utilize baselining research to develop a real time dynamic phase angle limit application that could be used to dynamically update phase angle limits for operations.
2. Extend the statistical control chart techniques to rate of change of phase angles for refinement, severity ranking and event location detection.
3. Extend the precursor research to assess combination metrics and their value in alerting operators to potential for extreme events.
4. Extend the statistical study into the other dynamic metrics such as oscillations and voltage and angle sensitivities.

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