May 10, 2011 Blackout of the Western and Central Upper Peninsula of Michigan

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Summary: On May 10, 2011 at approximately 3:30am the Western and Central Upper Peninsula of Michigan (U.P.) experienced a total electrical grid blackout within the American Transmission Co. (ATC) footprint. This event affected load within Upper Peninsula Power Company, Wisconsin Electric Power Company, and WPPI Energy Local Balancing Areas (LBAs) and was contained within the Midwest Independent Transmission System Operator (MISO) RC area. As in all blackouts, analysis and discussion can lead to a better understanding of this event and prevention from reoccurrence in the future. Beyond the usual detailed analysis lessons, this blackout is informative because it had several Phasor Measurement Units (PMUs) located in and near the event area that recorded GPS time stamped system conditions that accurately depicted the sequence of events. The PMU data appears to be much more accurate than typical SCADA recorded data used in traditional event analysis of such events. The event also gives insight and experience into dealing with NERC Event Reporting compliance requirements given in the NERC Electric Reliability Organization (ERO) Event Analysis Process – Field Test – Version 2 that was in place on May 10th, 2011 for a level 2 loss of load (greater than 300 MW).

Background: The Upper Peninsula of Michigan (U.P.) is geographically bounded to the north and west by Lake Superior and to the east by the Straits of Mackinac and Lake Michigan. The eastern UP is electrically connected with lower Michigan by two 138-kV underwater cables across the Straits of Mackinac. The central UP is electrically connected with northern Wisconsin by one 345-kV line and two 138-kV lines. Both of these 138-kV lines are located on the same support structures (common towers). The western UP is connected with northern Wisconsin by one 69-kV line and one 138-kV line. Following normal operating practices, the two transmission lines tying the central and eastern UP were being operated as normally open.

The total load in the western and central Upper Peninsula is typically 500–600 MW. Much of the load is industrial customers that include several mines. The mine load is typically between 200 to 300 MW. A multiunit coal fired power plant, located in the northern part of the UP, is the largest source of generation in the Upper Peninsula. This plant has a total capacity of approximately 400 MW.

The Event Details: To allow installation of system upgrades, ATC scheduled an outage on the 345-kV line connecting the UP to Wisconsin from May 9 to May 13. This was an approved outage based on ATC and MISO studies and policies. On May 10, at 03:25:08.811, ATC experienced a lightning strike to a tower, or shield wire, that caused an arc to flash across both B-phase insulators on a tower supporting the two 138-kV lines that parallel the out of serviced 345-kV line in northern Wisconsin and the central UP. Both 138-kV line terminals cleared correctly within 4.5 cycles. Since the transmission lines from the central UP to the eastern UP were open, as they normally are, this lightning stroke and resultant fault clearing left only the western 138 and 69-kV transmission lines connecting Wisconsin to the western and central UP. The remaining 69-kV line in the west tripped about half a second after the initiating lighting stroke due to frequency decay. About 2.5 seconds after the initiating lightning strike occurred the remaining 138-kV line in the western UP tripped. This completed the separation of the western and central UP from Wisconsin and the Eastern Interconnect. The eastern UP was effectively isolated from this event.

ATC event records indicated that the initiating lightning strike that caused the 138-kV lines to trip was 93 kA in magnitude, which is higher than what the lines were designed to withstand. Designing lines to withstand this large of lightning stroke is very challenging due to the poor soil grounding conditions in the local area. The total area load just prior to the outage was about 470 MW net. Local generation accounted for about 300 MW and about 170 MW was flowing north into the U.P. from Wisconsin.

The Midwest Reliability Organization (MRO) and Reliability*First* Corporation (RFC) Underfrequency Load Shed (UFLS) program, which is based on the adopted MAIN Guide 1B, was in effect at the time of the event. That program allowed for approximately 75 MW to be available for UFLS action within the island at the time of this event to arrest frequency decline. In addition to the load shed under the MRO and RFC UFLS program there was approximately an additional 110 MW of load shed via UFLS relays. These numbers indicate that the total UFLS within the event area would have been adequate to arrest and stabilize the island’s declining frequency after the initiating lightning strike and resultant island formation. However, the initial stage of declining frequency caused a large environmental emission control motor at the sole large coal fired generation plant to trip offline before completion of the UFLS program. This motor trip eventually caused two generator units, which had a combined output just prior to the event of about 120 MW, to trip off line. Some of the remaining online generators quickly ramped up their output level to arrest the frequency decay caused by the loss of the two generators. The boiler of one of the remaining online generators could not sustain the increased level of output long term and eventually caused the unit to trip offline. The remaining large coal unit later tripped due to the sustained low frequency.

During the event, parts of the isolated island saw extremely low voltages; this caused some breakers within the island to trip. This was due to their line protection relays interpreting the low voltage and increased current conditions as a three phase fault. These breakers opening resulted in the island splitting into two parts prior to their total collapse. The elapsed time from the initial lightning strike to the total area blackout took 4 minutes and 14 seconds.

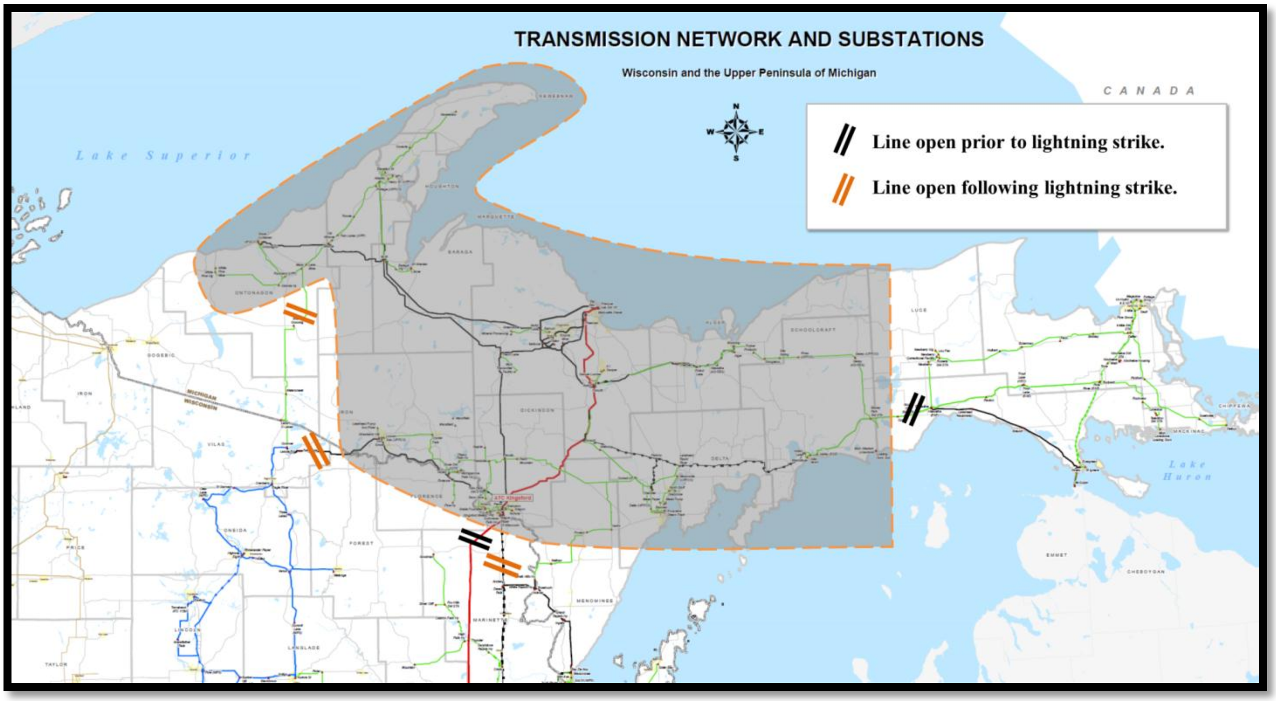

Figure 1: Area of UP Blacked Out on May 10, 2011

Note: Lines open prior to the lightning strike and those that followed it that electrically isolated the area

The following figures show the frequency versus time for the event as previously described. Figure 2 shows the PMU recorded frequency within the island from event initiation to collapse.

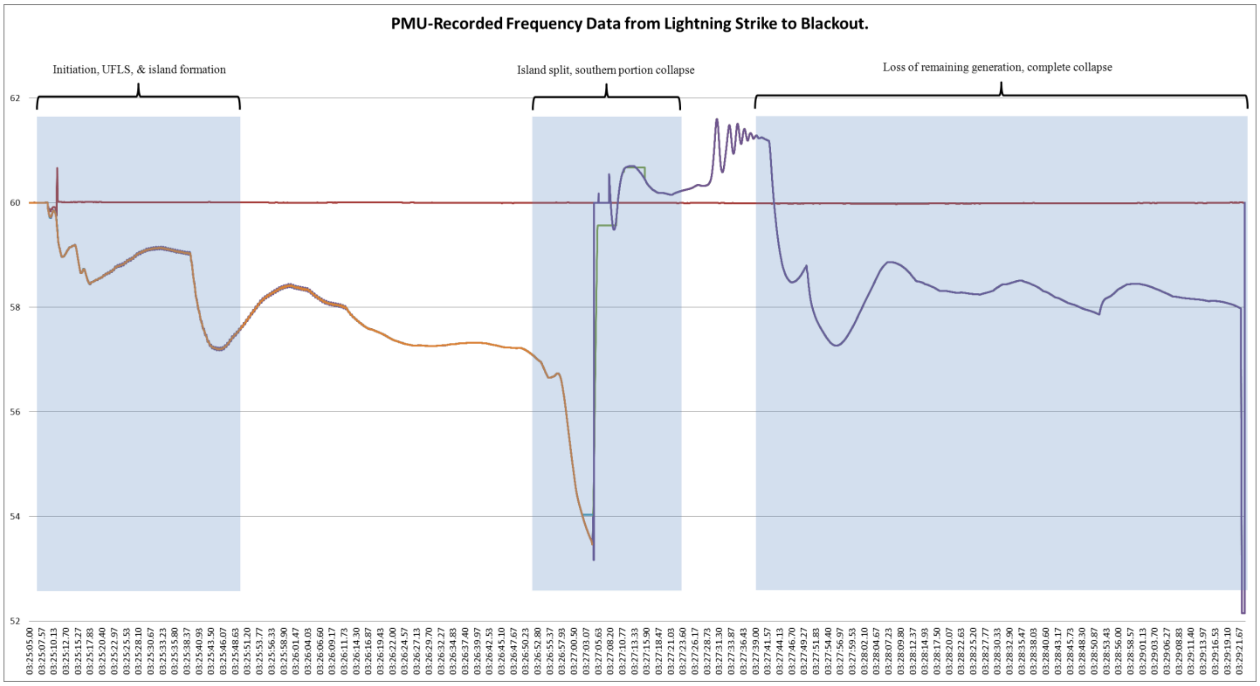

Figure 1: PMU-recorded frequency for the May 10, 2011 event

Figure 3, below, shows the PMU frequency data during the first 40 seconds following the lightning strike. Note the frequency increases at times after load shed, hence after the event there were times that the generation exceeded the load and the island was tending toward stable operation.

Figure 3: PMU-recorded frequency data during initial 40 seconds following lightning strike

ATC Control Center: Within ten seconds of the lightning strike that caused the two 138-kV lines to open the ATC System Control Center had over twenty related alarms from the area and within a minute it had over a hundred. Alarms continued to come in throughout the event eventually totaling over 3000 once the island was blacked out.

At the time the ATC System Operator realized a large disturbance had occurred in the U.P., but did not immediately know the exact location or the boundaries of the outage. The operators' main tool used during this time to determine the boundaries of the blacked out area was a static one-line wall map board with lights that indicated:

- Line flows that were zero
- Generators that were off line
- Bus tie breakers that were open
- Very limited voltage, power flow, and frequency analog data

A review of this board indicated an area in the U.P. was indeed blacked out and it appeared to be growing. Within minutes several hundred more alarms were received by the ATC EMS system, and alarms continued to come in for the next hour. The Contingency Analysis programs were not available at first due to the non-convergence of the state estimator solution. This non-convergence was caused by the sudden loss of so much incoming data. ATC did have a one-line voltage diagram showing bus voltages (and capacitor status) that uses RTU data as its input. Using this display the ATC Operator had bus voltage indication for the entire area and used it to determine the extent of the blackout area within a few minutes of the island collapse.

MISO Control Center: Within one minute of the initiating lightning stroke the MISO SCADA system recorded over 370 individual alarms. Multiple MISO tools and displays indicated the loss of transmission and generation equipment had occurred in the U.P. including the SCADA Alarm Summary Display, the SCADA USA Overview Display, the Generation Monitoring Tool, the Transmission Delta-Flow Monitoring Tool and the Equipment Outages Display. The MISO East RC reviewed these tools to determine the extent of the outage. The MISO operators made or received phone calls from the various impacted entities associated with the blackout.

Advantages of PMUs over SCADA: ATC has several GPS-synchronized PMUs in the affected region. The PMUs have a sampling rate of 30 times per second and each data point has a synchronized GPS time stamp. The traditional RTU SCADA data has a sampling rate of once every 4 seconds with no GPS time stamp

The GPS time synchronized data from these PMUs was used to accurately sequence events from non-synchronized recording devices in the island (including many of the protection relays and digital fault recording devices). The PMU frequency data was also used to correlate underfrequency load shed scheme operations.

In order to illustrate the benefits of having PMU data available, charts are included below to demonstrate the superiority over SCADA data. As seen in Figure 4, PMU-recorded frequency data compared to traditional SCADA information, the general trend of the SCADA data does follow the PMU curve but lags the actual event data by seconds, and does not possess the granularity to capture the small changes in frequency that were needed to accurately correlate event data. Figures 4, 5, 6, and 7 give a comparison of the system frequency of the May 10th event between the PMU and SCADA data. Several major transmission and generation events and several underfrequency load shed events occurred well before the SCADA data indicates these events. While SCADA provided a similar trend as the PMUs, it lacks the details needed to adequately determine when each significant event occurred.

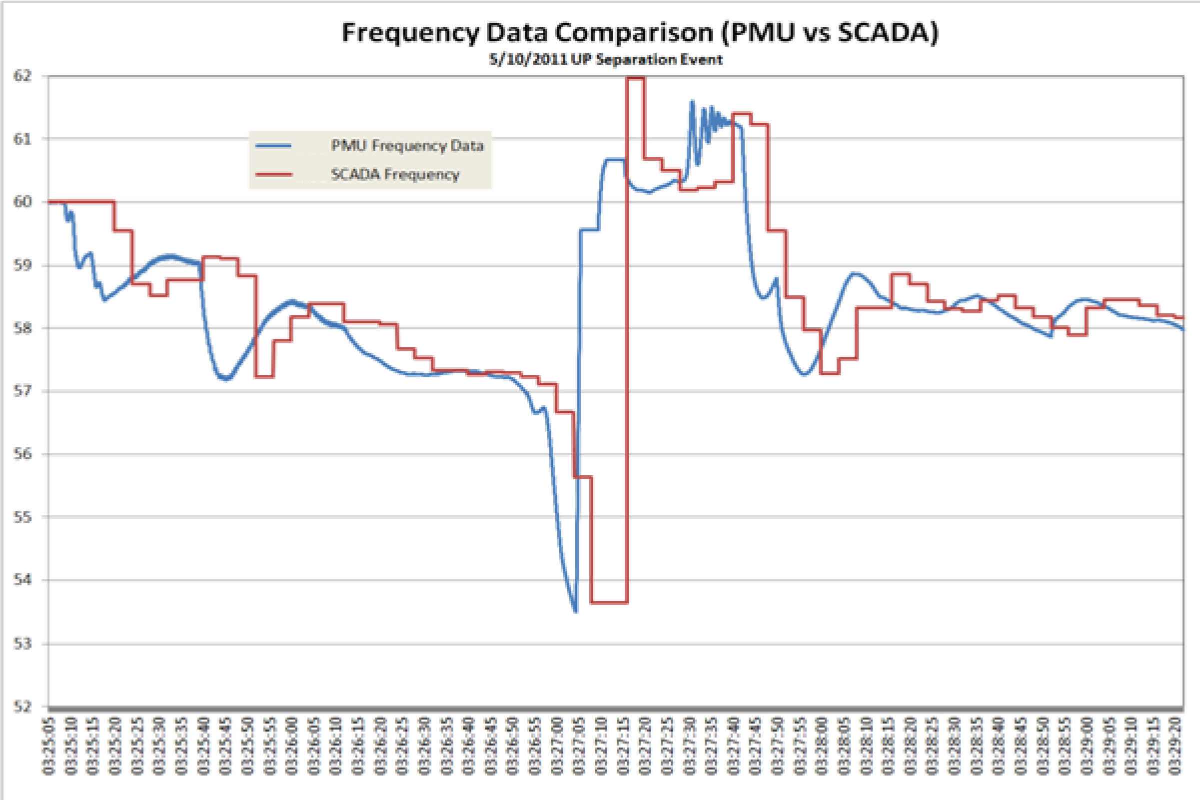

Figure 4: PMU-recorded frequency data compared to traditional SCADA information for the entire event

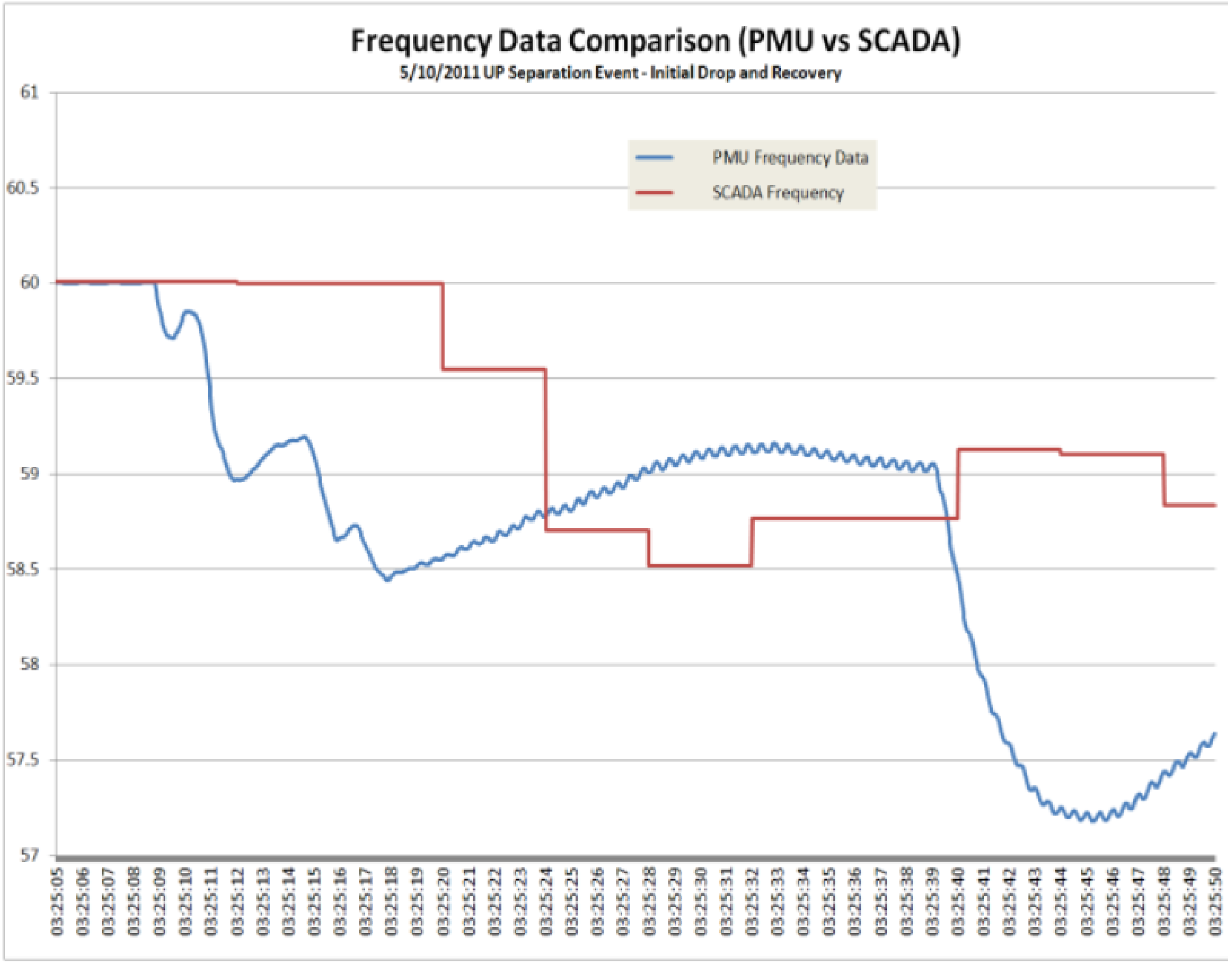

Figure 5: PMU-recorded frequency data compared to traditional SCADA information for the first 40 seconds of the event

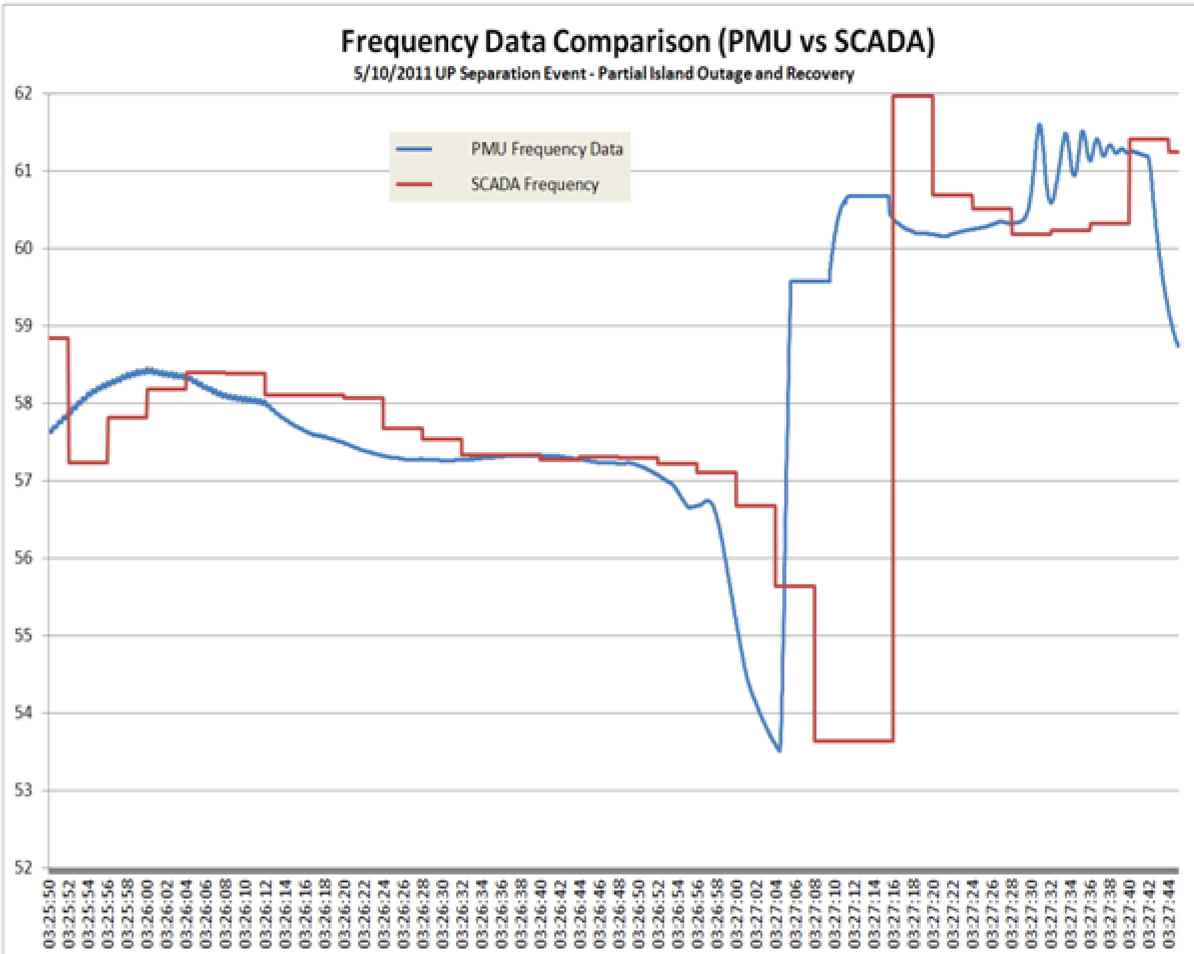

Figure 6: PMU-recorded frequency compared to traditional SCADA information during the UP island split

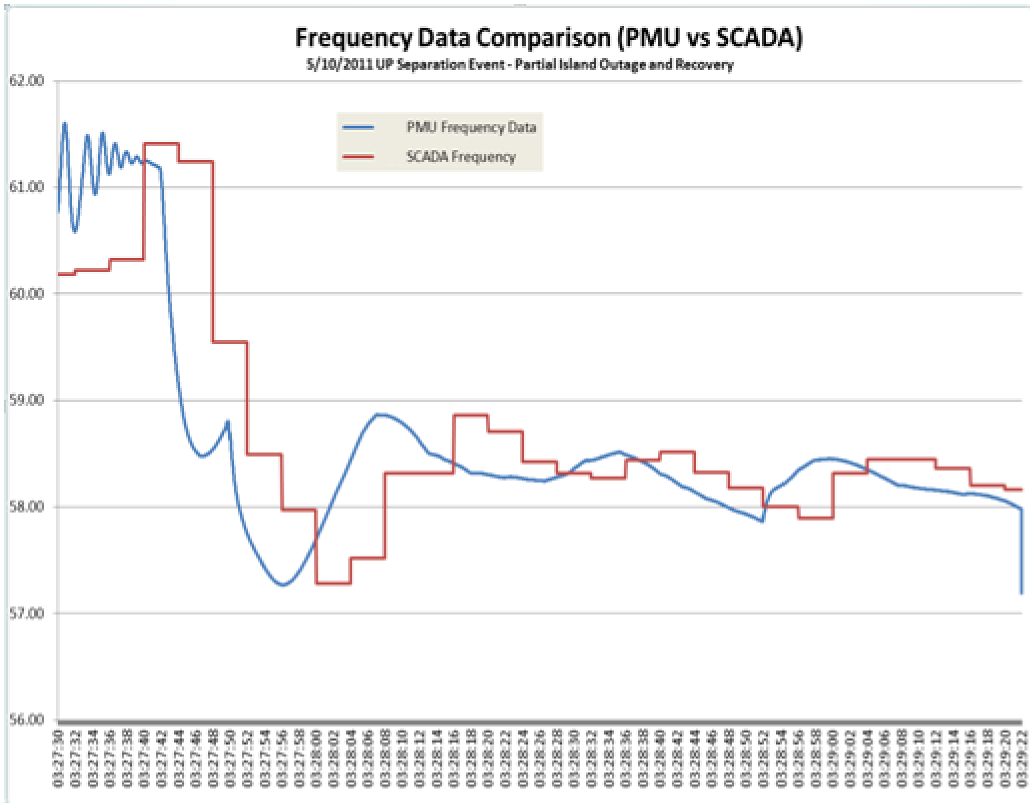

Figure 7: PMU-recorded frequency compared to traditional SCADA information during the last two minutes of the event

Event Reporting: The Regional Reliability Organization (RRO) can request a report any time an underfrequency load shedding event, per PRC-009-0, or loss of load event occurs as applicable in the NERC ERO event analysis process guidelines. The NERC ERO Event Analysis Process – Field Test – Version 2 that was in place on May 10th, 2011 classified the May 10, 2011 event as a level 2 loss of load (greater than 300 MW).

The UFLS plan is owned by the area RROs and it is the responsibility of the LBA to comply with the approved plan. For this event, ATC agreed to coordinate the data gathering and filing of the required reports in collaboration with the entities involved.

ATC and the collaborating entities established and agreed to a work plan with the RROs that allowed the reporting requirements to be fulfilled in approximately 12 months after the event occurred. It is very important to record and save as much of the data surrounding the event as quickly as practical after it occurs. Initially, high importance should be placed on determining the sequence of events; what happened and when and not necessarily on why. Later phases of the reporting process allow for the root cause analysis to be performed.

Summary: There are natural events that occur despite the industry's best efforts to mitigate them. These events have the potential to cause blackouts or other disturbances. PMU's can offer great advantages in post event analysis to determine the sequence of events and root causes of the disturbance. The post event reporting requirements can be rigorous and it is important to develop a reporting plan immediately after the event and begin work as soon as practical.