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Post-Event Analysis of a Compound Event in the ERCOT System Using Synchrophasor Data

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SUMMARY

This paper presents experiences in the use of synchronized phasor measurement technology in the Electric Reliability Council of Texas (ERCOT) interconnection, USA. The paper discusses the post-event analysis of a compound event in the ERCOT system involving a fault, which, due to relay mis-operation, induced a loss of generation event.

The relay mis-operation in response to the fault tripped one of two 345kV circuits interconnecting a generating station to the ERCOT transmission system. Thereby an imbalance occurred between the loading of the generator and the mechanical energy of its turbine system, which led to a rapid reduction in the power output of the generator as the turbine controls closed the intercept valves to protect the equipment from over-speed.

This paper presents the insights gained from studying the synchrophasor data and points out the various indicators that determine the characteristics of the event. The owners (also the operators) of the effected equipment corroborated the conclusions drawn from the post-event analysis. This paper demonstrates a new use case for synchrophasor technology that helps identify and correct possibly incorrect operation of the equipment.

KEYWORDS

Synchrophasor – Phasor Measurement Unit – Phasor Data Concentrator – Frequency – Impulse – Ramp – Power Load Unbalance – Voltage – Phase – Fault.

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1. Introduction

The Electric Reliability Council of Texas Inc. (ERCOT) serves as the independent system operator (ISO) for most of the state of Texas. The ISO manages delivery of electric power to 24 million customers in Texas, representing 85 percent of the state's electric load and 75 percent of Texas land area. The ERCOT electric grid consists of around 41,500 miles of transmission and more than 550 generating units [1]. The total installed generation capacity for peak demand in ERCOT is 74,000 MW and its recorded peak load is 68,305 MW. There is more than 11,000 MW of wind generation capacity installed and operating in the ERCOT market, and in March 2014, the total wind generation reached a record 10,296 MW, which was 29% of the load at the time [2].

Most of the generated power in ERCOT is consumed in industrial and urban load centers in East, Central and South Texas, while most of the wind energy is installed in the north-west part of the state because of abundant wind resources there. This separation between resources and load centers has created some unique challenges in the integration of renewable resources, and in meeting the growing demand for power while also effectively ensuring the reliability of the grid [3 – 5].

Since synchronized Phasor Measurement Units (PMUs) were first introduced in the early 1980s, they have been recognized as suitable tools to modernize power system monitoring and control [6]. In the recent years, various applications of PMUs in power systems have been studied and the technology is becoming popular due to its versatility [7, 8]. Applications of phasor measurements have been extended to power system monitoring [9, 10], protection [11] and control [12].

Recognizing the potential benefits of synchronized phasor measurements, or synchrophasors, ERCOT started a collaborative effort in 2008 to implement this technology in its Operations and Planning processes. This effort, coordinated by the Center for the Commercialization of Electric Technology (CCET) under a grant from the Department of Energy, has engaged various entities, including ERCOT Transmission Service Providers (TSPs) and a software application provider [13].

As PMUs have been installed across the ERCOT grid, several real-time and off-line data processing and analysis tools have been acquired for ERCOT engineers to monitor and study the incoming synchrophasor data. Analyses using the synchrophasor data have indicated that synchronized phasor measurements can greatly improve both ERCOT Operations procedures and Planning studies. [14] gives the details of some of the applications of synchrophasor data in ERCOT.

This paper presents a real-time example of the application of PMU data for post-event analysis of a compound event in the ERCOT system. Section II describes the present state of the ERCOT PMU network, including the locations of the PMUs and the structure of the communications systems. Section III presents a specific example of the application of synchrophasor data in ERCOT for post-event analysis Section IV summarizes the conclusions arising from this analysis.

2. The ERCOT PMU Network

This section discusses the locations of PMUs and their effects on different applications in ERCOT. Also presented is the current state of the communication network tying the PMUs and Phasor Data Concentrators (PDCs) together.

2.1. Present PMU Locations in the ERCOT Grid

In principle, PMUs should be installed across the ERCOT transmission grid to provide good observability for the entire network. Currently, synchrophasor data is available only from PMUs installed on the networks of TSPs participating in the collaborative effort (discussed in Section I). Fig. 1 shows the geographical locations of the existing PMUs in the ERCOT system.

At the time of writing this paper, there are 76 PMUs connected to ERCOT PMU network. That number is expected to go up to at least 100 PMUs in the coming months. The data presented in this paper was obtained from the installed PMUs shown in Fig. 1. Note that not all PMU data sources were always available for the recorded events due to communication constraints or outages.

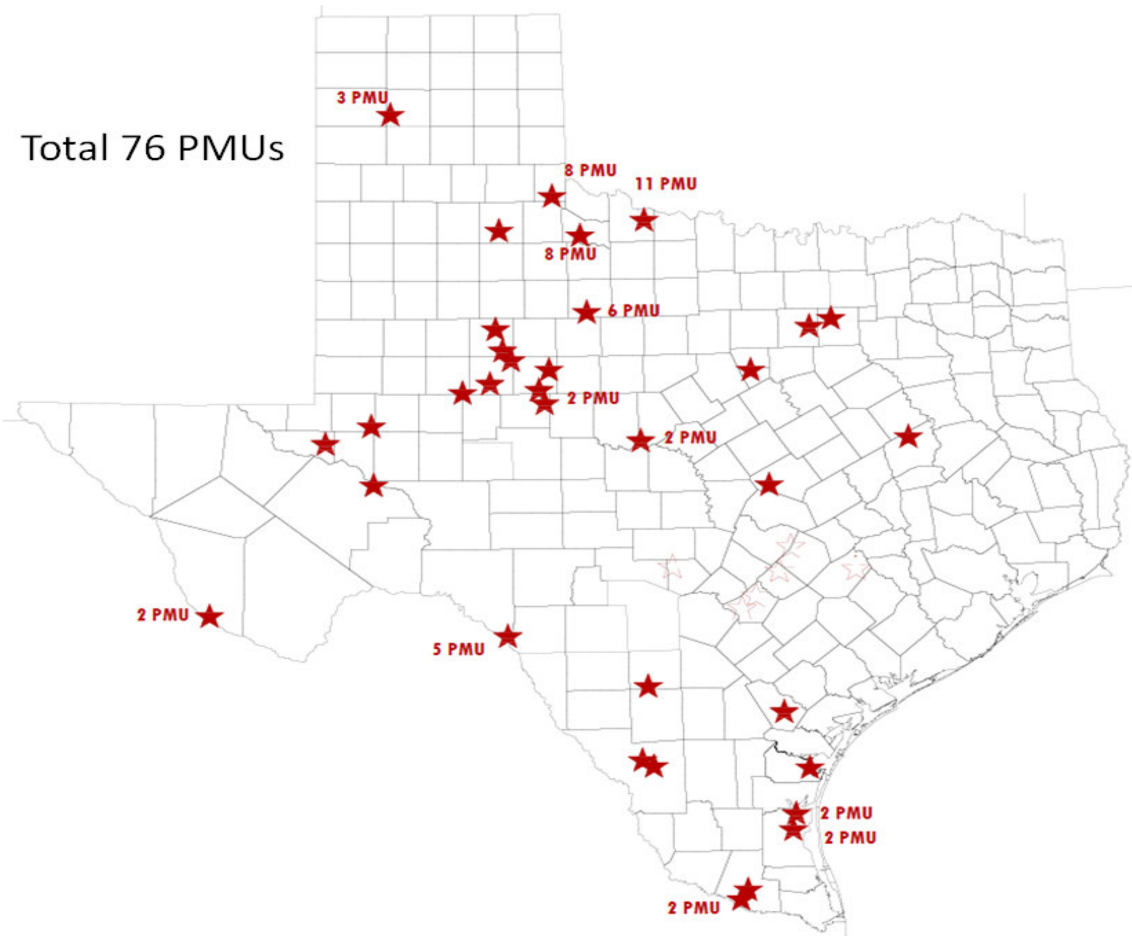

Fig. 1 PMU locations in the ERCOT grid

Although more PMUs will provide a clearer overall picture of the grid with a resolution of 30 samples per second, even the limited number of PMUs in the current ERCOT grid have shown that they can be valuable in post-event dynamic analysis, real-time small signal stability monitoring and generator model validation [14]. PMUs installed in the West and North areas (see Fig. 1) allow ERCOT to monitor the stability conditions on the interface between these two regions. In addition, as most of wind generation is installed in West Texas, the data from PMUs located close to wind power plants has also helped ERCOT validate dynamic wind generation models [14].

2.2. Synchrophasor Data and Communications

A communications network has been built to transfer synchrophasor data from the individual PMUs to the ERCOT control center, where the incoming data is streamed to real-time applications and archived for off-line studies.

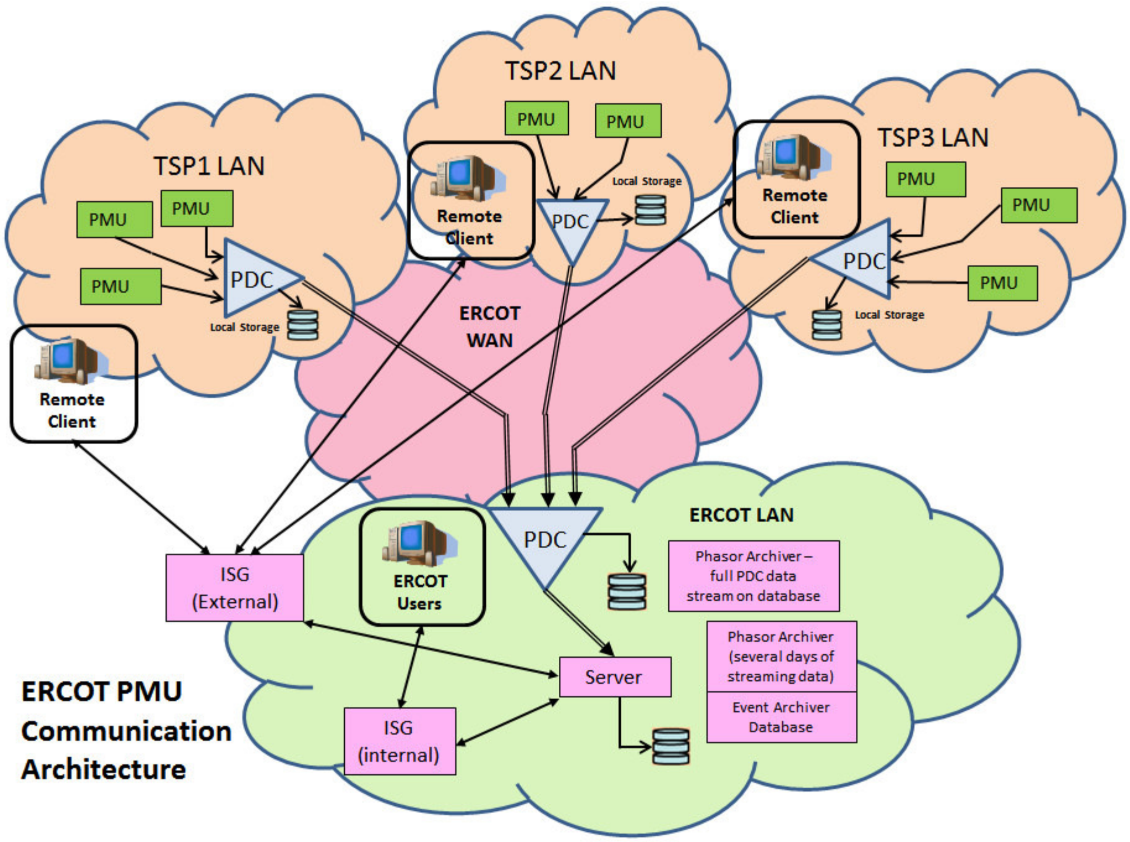

Fig. 2 The Synchrophasor data communication network

As shown in Fig. 2, participating TSPs gather the data packets from individual devices in their PDCs where it can be made available for real-time visualization and also for local data storage. The ERCOT PDC receives the data from the respective PDCs of the TSPs. The ERCOT PDC synchronizes this data using the attached time stamp, and provides the data stream to real-time visualization applications in the ERCOT control center and also archives the data for offline studies. The ERCOT Secured Private Wide Area Network (WAN) forms the basis for all data communications between ERCOT and the participating TSPs.

For data management, both the TSPs local PDCs and the ERCOT PDC archive the phasor data. ERCOT saves streamed synchrophasor data up to 400 days, and archives select event data over a longer timeframe. A real-time application installed in the ERCOT control center monitors the incoming stream of synchrophasor data and automatically creates event files when it detects a disturbance which may then be archived.

3. Application of PMU Data for Post-Event Analysis

This section presents the post-event analysis conducted by ERCOT engineers for a compound event on the grid. In the process of analyzing a loss-of-generation event using PMU data, ERCOT engineers discovered other disturbances immediately before the loss of generation. This triggered a more in-depth analysis of these disturbances. Using the work detailed by A. Allen *et al.* in [15], the various trends in system frequency were analyzed. The event began with a phase-to-ground fault (determined by PMU frequency and voltage), which was followed by three separate frequency ramps. Since SCADA telemetry indicated that only the third frequency ramp was caused by a generator going offline, ERCOT requested information from the operator of the power plant about a possible load rejection/imbalance event. The operator confirmed that the load imbalance had indeed happened while the TSP in the area confirmed the occurrence of the fault as well as a relay mis-operation in response to the fault at the Point of Interconnection (POI) of the generating station.

Fig. 3 shows a one-line of the region. A phase-to-ground fault on a 138 kV bus section at the sub-station marked as S2, one bus away from the POI of generating unit G1, was followed by mis-operation of relays at the POI (sub-station S1 in the one-line). The clearing of the fault caused the 345kV circuit connecting the sub-stations S1 and S2 to be tripped, causing a transient imbalance between the loading and mechanical power of unit G1. This finally led to the tripping of the generator and a total frequency swing of 0.217 Hz.

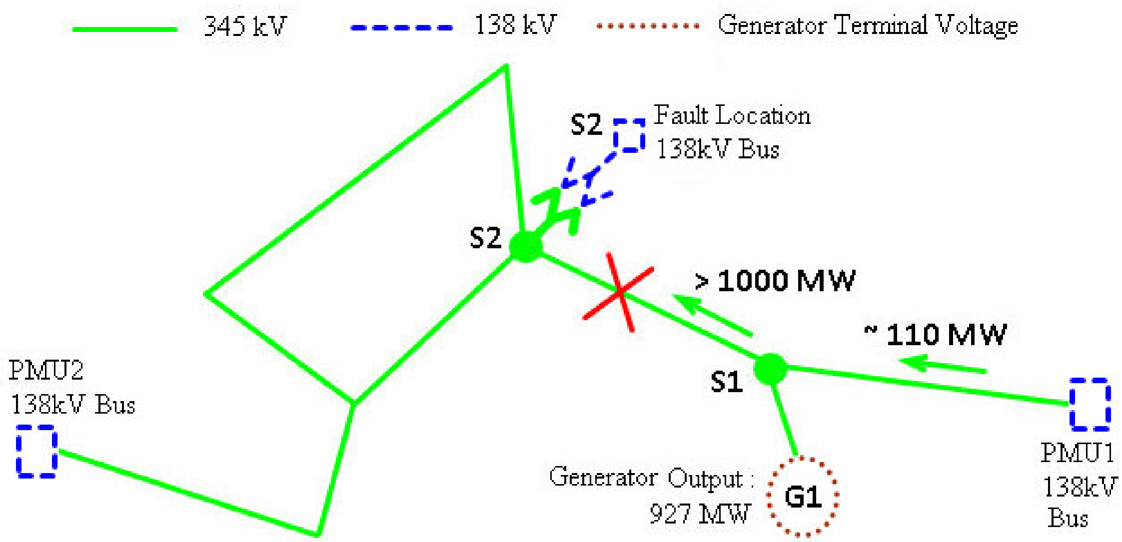

Fig. 3 One-line of the 345kV system near the event and the relative location of the PMUs

3.1. The Power Load Unbalance (PLU) relay

The PLU relay is designed to rapidly close control/intercept valves under load imbalance conditions in order to reduce generation and protect the turbine from an over-speed event. The relay compares the loading on the generator to the mechanical energy in the turbine [16, 17] and trips if the difference is more than a set percentage, typically 40% or 0.4 per unit, and the load decreases faster than a set rate, typically equivalent to going from rated load to no load in 35 milli-seconds [16]. Once the unbalanced condition has cleared and a set time delay has passed, the PLU relay is reset and the intercept valves open, allowing load to be restored to the generator. However, the load reference used by the valves does not return to the value before the event, but remains at the value reached when the PLU relay is reset [16].

3.2. System Frequency

Fig. 4 shows the frequency trend captured by the PMUs on the ERCOT grid over the course of this event. A. Allen *et al.* classified frequency trends captured by PMUs during various types of system events into three categories [15]:

1. Frequency Impulse
    a. Half-Impulse
    b. Full-Impulse
2. Frequency Transient

3. Frequency Ramp

The frequency characteristic (Fig. 4) recorded by the PMUs on the ERCOT system shows two of these three distinct characteristics – the Impulse and the Ramp.

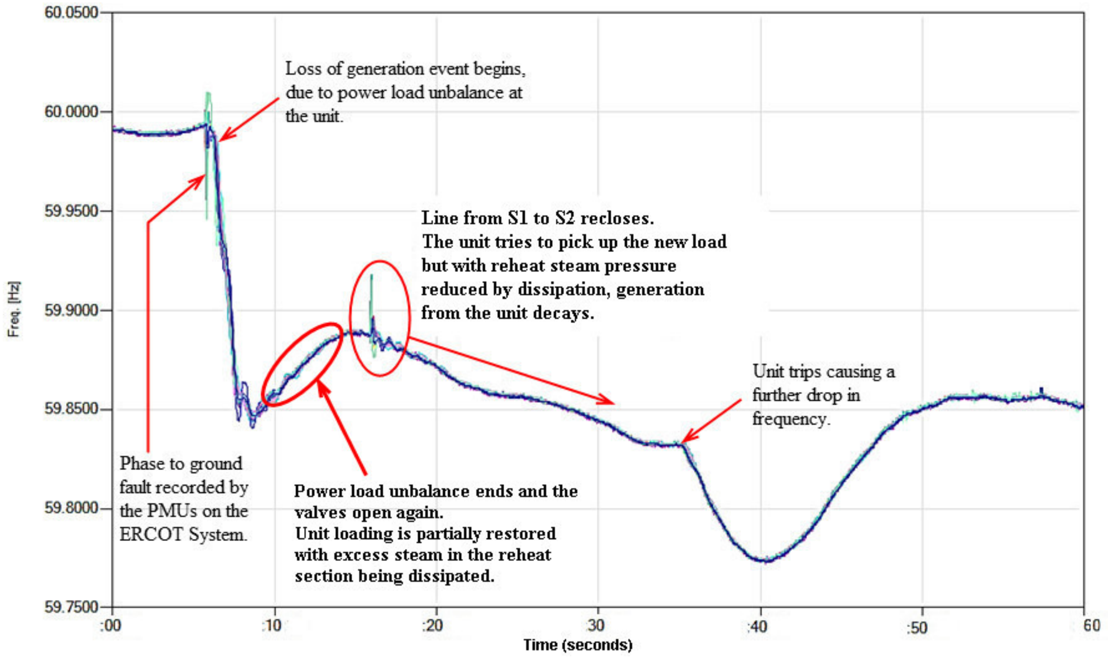

Fig. 4 System Frequency recorded by the PMUs on the ERCOT Grid during this event

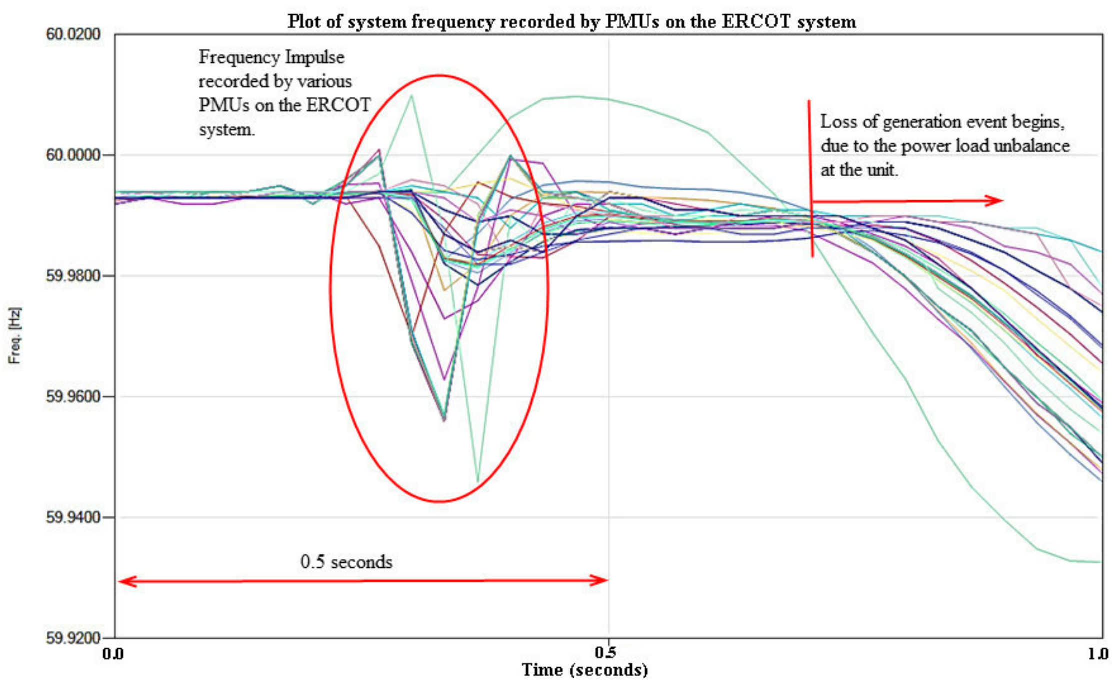

Fig. 5 Representation of a system fault in the measured frequency from the PMUs

3.3. System Phase-to-Ground Fault

The phase-to-ground fault on the system occurred approximately 30 cycles before the onset of the loss-of-generation event. This is seen to be represented by one of the characteristic frequency trends identified in [15] – specifically, the half/full impulse (see Fig. 5).

The authors note here, that such a frequency impulse from PMU data records is not a characteristic of the physical/rotational inertia of the system, but rather a result of the fact that the frequency measured by a PMU is a function (derivative) of the voltage phase angle of the point of measurement [6].

That the event which occurred was indeed a fault was confirmed by examining the voltage magnitudes at the two PMUs (PMU1 and PMU2) identified in the one-line of the region. As expected, there is a sharp (near instantaneous) drop in the voltage recorded by the PMUs, which is the characteristic of voltage near a fault.

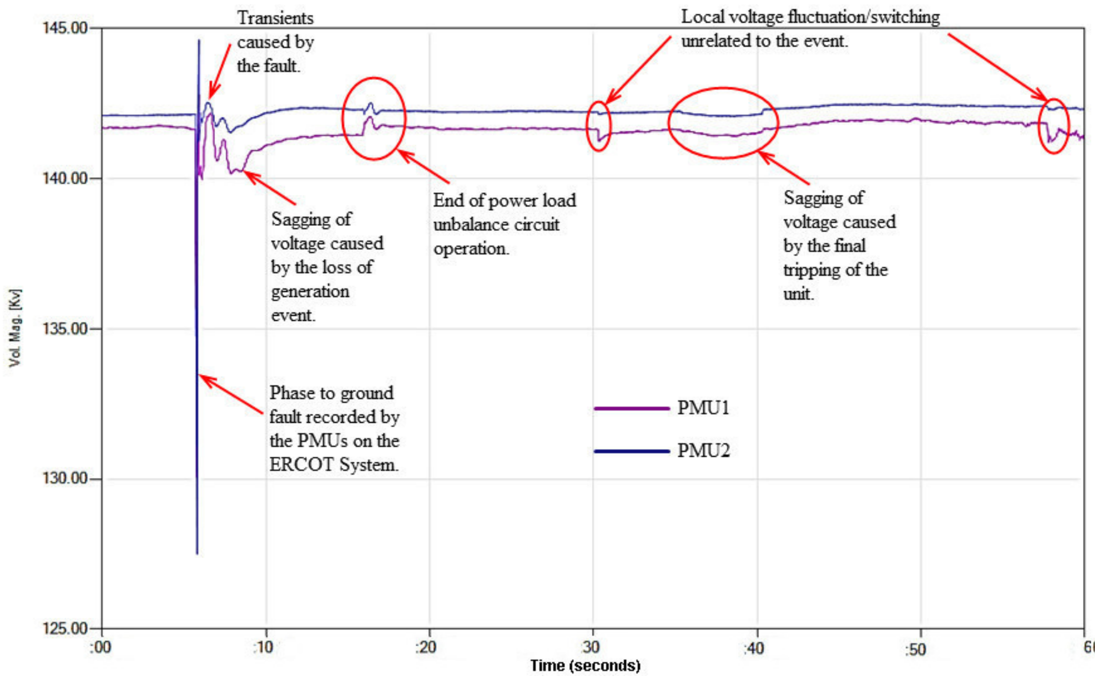

Fig. 6 Phase Voltages measured by PMUs near the event

3.4. Loss of Generation

The loss of generation event can be easily identified from the frequency trend recorded by the PMUs. Following the classifications in [15], the frequency ramp, marked FR1 in Fig. 7, corresponds directly with the first loss of generation event.

As Fig, 4 shows, there were three such ramp events involving the loss of generation in this compound event. They are marked FR1, FR2 and FR3 in Fig. 7. FR1 and FR3 were caused by near-instantaneous loss-of-generation events and FR2 was the slow decay of frequency over several tens of seconds that happened in the interval between FR1 and FR3.

Following the fault on the system and clearance with the tripping of the line between sub-stations S1 and S2 in the one-line, the system experienced the first loss-of-generation event. In this first event, the generation from the unit 'G1' dropped by approximately 575 MW, causing the frequency to decline from 59.99 Hz to 59.846 Hz, a drop of 0.144 Hz, in around 3 seconds. With the loading on the unit being drastically reduced due to the loss of one of the lines interconnecting the unit to the ERCOT system, a power load unbalance greater than 40% was detected by the generator-turbine control system. This caused the activation of the PLU circuit, leading to the steam intercept valves being rapidly closed in order to limit the turbine mechanical energy and protect the generator from over-speed. This was the cause of the first frequency event detected by the PMUs on the ERCOT synchrophasor network. However, the unit did not go offline during this event.

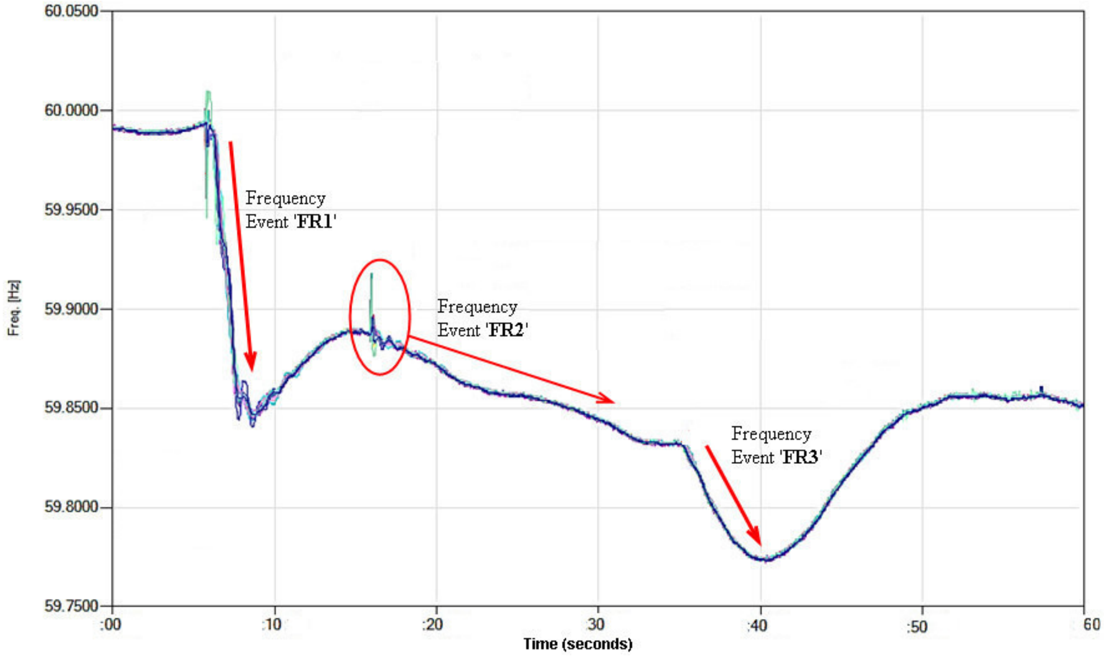

Fig. 7 Three frequency sub-events 'FR1', 'FR2' and 'FR3'

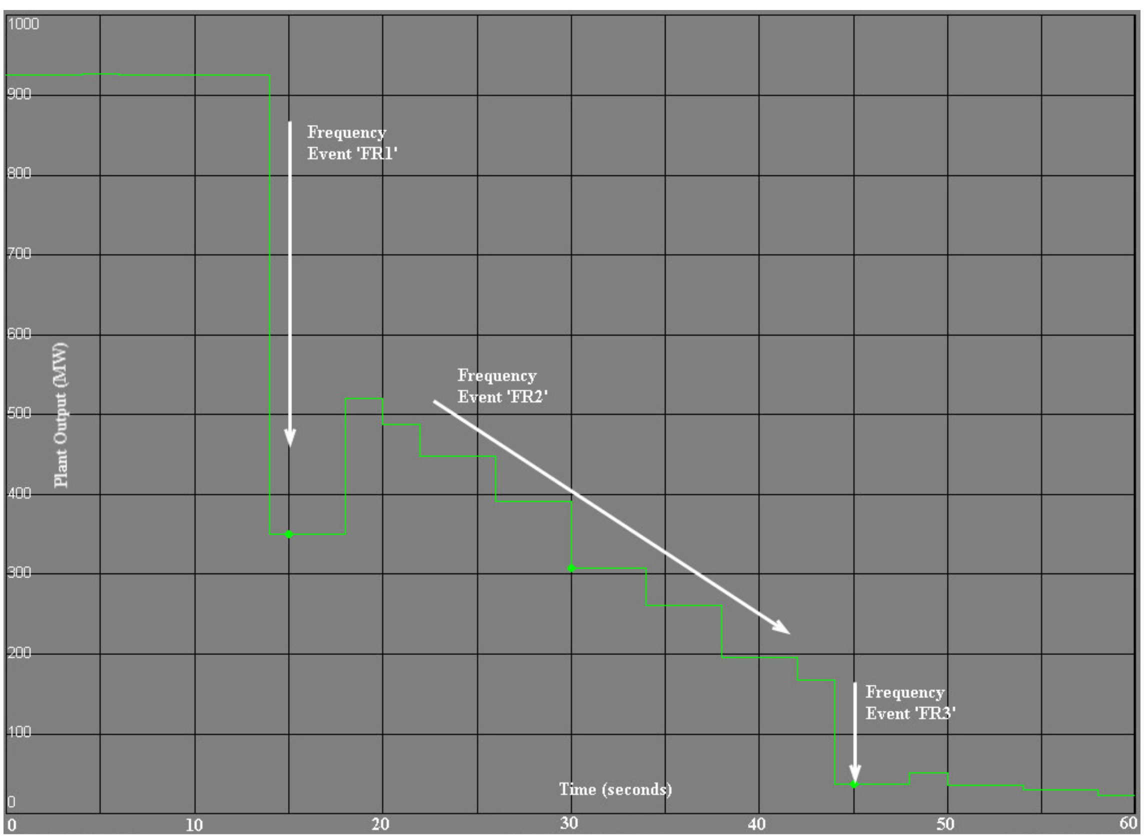

Fig. 8 Unit output as telemetered by SCADA (PI chart, times are not exact)

Following the arrest of frequency decline by the system's inherent inertia, the governor response of the system set in with AGC acting to restore system frequency to its pre-event state. The PLU condition cleared (difference between mechanical energy and electrical load reduced below 40%) and following the time delay, the PLU control circuit disengaged and the intercept valves were opened allowing the generator to take on load again.

Approximately 10 seconds after inception of event FR1, the line connecting stations S1 and S2 reclosed. This appears as the second impulse in the frequency demarcated in Fig. 4 as the reclosing of the line from S1 to S2. That this impulse frequency did indeed correspond to a reclosing event and not a fault was confirmed by an examination of the voltage magnitudes of PMU1 and PMU2 at the corresponding time-stamp as shown in Fig. 6.

By the time the line reclosed, the unit loading had been partially restored to approximately 500 MW (according to SCADA telemetry from the unit, see Fig. 8). The excess steam that was trapped in the reheat section while the PLU circuit was active was dissipated. Therefore, when the loading on the unit increased after the reclosing, there was not enough pressure in the reheat to sustain it and generation decayed once again, which can be seen as the slow ramp down of frequency in Fig. 7 marked as event FR2'. This is also referred to as 'run back'.

Finally, due to the generation becoming too low, the unit tripped leading to the second frequency event detected by the PMUs designated as FR3.

4. Conclusions

This paper presents a real-time example of using synchrophasor data to perform post-event analysis of complex events in the ERCOT system. Aided by the insight obtained from analysing the synchrophasor data, engineers at ERCOT were able to communicate with the transmission owner as well as the owner/operator of the power plant and confirm the facts.

Responses from the transmission owner allowed ERCOT engineers to finalize the correct sequence of relaying events and establish the cause for the relay mis-operation. Detailed responses from the plant operator established the PLU circuit parameters and showed that the PLU operated as designed. However, the loss of a unit, which was not in the clearing zone of the fault, has caused the plant operator to start discussions with their vendor to determine if the loss of generation was necessary and whether the PLU parameters need to be changed.

This paper demonstrated a new use case for synchrophasor technology that helps identify and correct possibly incorrect operation of the equipment. Such event analyses with synchrophasor data are now performed regularly at ERCOT for a variety of system disturbances. These analyses have helped to do model validation and correct generator control-system parameters, if required [14].

The analysis presented in this paper also has useful information for planning studies at ERCOT. These studies have not commonly accounted for the possibility of contingent loss of generation due to power load unbalance caused by a fault near the POI of a generator. One conclusion of this study was to investigate the possibility of other generators on the system being tripped during a fault that should not necessarily isolate the generator/plant from the grid.

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