Wide-Area Measurements to Improve System Models and System Operation

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Abstract

This paper presents collected events to demonstrate the use of synchrophasor data to update and improve system models and system operation. Examples are given of responses to events captured using wide-area synchrophasor measurements. Phase angle, frequency, and voltage responses are displayed with discussion of the events, synchrophasor data views, and insights to be gained from the different data types. This paper advances the understanding of wide-area measurement systems, which provide the newest development in system monitoring.

1 Introduction

Availability of wide-area measurements of frequency, voltage and current magnitudes, and especially phase angle has increased dramatically in recent years. Low-cost, highly accurate clocks that synchronize these measurements have significantly changed the dynamic of data collection. The time-coherent nature of these measurements has led to the general name of "synchrophasors" to describe these data.

The existing approach, supervisory control and data acquisition (SCADA) systems, has much lower data rates than synchrophasors. Furthermore, the SCADA architecture is based on sequential scanning and has no inherent time synchronization of the collected data. This means that angle measurements are not time-aligned for display and analysis. With new generation sources, such as electronically interfaced wind generators, and the associated high-speed dynamics seen in the electric power system, the fast 50- or 60-message-per-second sample rate and time-stamped nature of synchrophasor systems provide a more appropriate approach to data collection for system operation.

Three system events are discussed in this paper: a frequency step due to loss of generation, a line trip, and the power system response after an earthquake. These events were visualized in real time using a synchrophasor system available over the public Internet. In this paper, the system architecture is explained and then each of the events is analyzed.

2 System architecture

Since 2003, a system for collecting and displaying synchrophasor information from around the world has been in service using the Internet. The phasor measurement units (PMUs) are located in offices, and the measurements are from the wall outlet level. Wall outlet data have proven useful for many applications such as oscillation analysis, inertial response estimation, event analysis, and phase angle base lines [3].

Fig. 1 shows the North American portion of the system architecture. Measurement devices are also placed in Europe and more are planned. Relays operate as PMUs and are directly connected to each wall outlet. The synchrophasor data are sent using the IEEE C37.118-2005 communications standard over a virtual private network (VPN) [4]. The connection type is Transmission Control Protocol (TCP), which provides robustness against dropped packets. At the data collection site, a phasor data concentrator (PDC) time-aligns the data. This compensates for communications and processing latencies in the network. Finally, data are archived and visualized with a software situational awareness package that is optimized for the unique characteristics of synchrophasor data. The data are then published for display over the Internet and are accessible with any standard web browser.

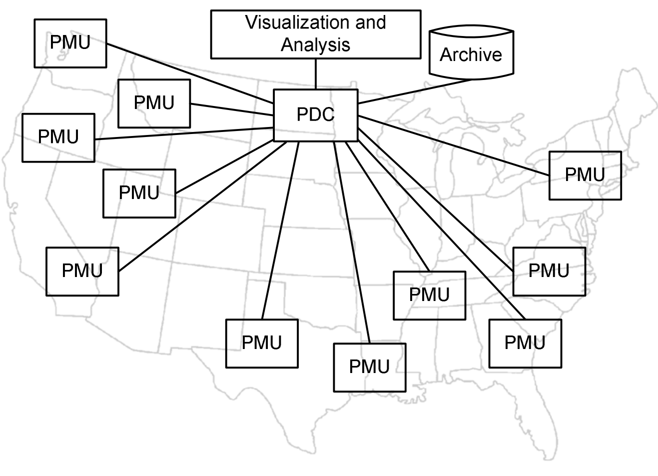

Fig. 1. Wide-area, time-synchronized measurement system.

3 Inertial response

The high synchrophasor sample rate is ideal for analyzing generator tripping events. On January 21, 2012, the Texas electrical system experienced a generator outage. Fig. 2 shows the real-time synchrophasor data that were recorded by the system of Fig. 1. The upper half of the figure is the frequency at Boerne, Texas, and Houston, Texas. The lower half of the figure is the phase angle between Boerne and Houston. By analyzing these synchrophasor data, information about system inertia, amount of generation lost, and other system parameters can be learned. First, consider system inertia. The equation of motion, (1), for a synchronous machine relates change in frequency to torque [5].

$$J \cdot \frac{df}{dt} \propto Tm - Te \tag{1}$$

The rotational rate of change, df/dt, of the machine is proportional to the difference between the mechanical input torque to the machine, *Tm*, and the electrical load on the machine, *Te*. The rotational rate of change is scaled by the moment of inertia, *J*, which has units of kg • m^2. A normalized inertial constant, *H*, with units of seconds, is often used in place of *J*. The inertial constant *H* is defined in (2).

$$H = \frac{2\pi^2 \cdot J \cdot f^2}{VA_{base}} \tag{2}$$

Combining (1) and (2) and converting torque to power by multiplication with the rotational frequency give a relationship for the inertial constant.

$$H = \frac{(Pm - Pe) \cdot f}{\left(2 \frac{df}{dt} VA_{base}\right)} \tag{3}$$

Consider (3) in light of the step response shown in Fig. 2. Because of the high sample rate, the rate df/dt is easy to measure. Notice that the high sample rate shows that the rate of change itself changes. Initially, the frequency decays with a high rate of change, and then the rate slows down and stops. The reason for this is the governor response of the generators, which arrests the changing frequency and brings it to a constant value. Therefore, the most accurate place to measure df/dt for estimating inertia is toward the decay initiation. Measuring df/dt at a specific instant on the slope is enabled by synchrophasors. Equation (4) provides the estimated df/dt obtained by measuring the slope of the frequency line in Fig. 2.

$$\frac{df}{dt} = -0.05 \text{ Hz/second} \tag{4}$$

Several parameters of the Texas electrical system are not known to the authors, but when synchrophasors are applied in a specific utility, these parameters are known. Therefore, without loss of generality, this paper assumes some values with the understanding that in a utility application the correct values are applied and the accuracy of the results improved accordingly. For the event on January 21, the Electric Reliability Council of Texas (ERCOT) publicly posted the total load at 31.275 GW [2]. Substituting df/dt and VA_{base} into (3) results in the following relationship:

$$H = (19.2 \text{ seconds/GW})(Pm - Pe) \tag{5}$$

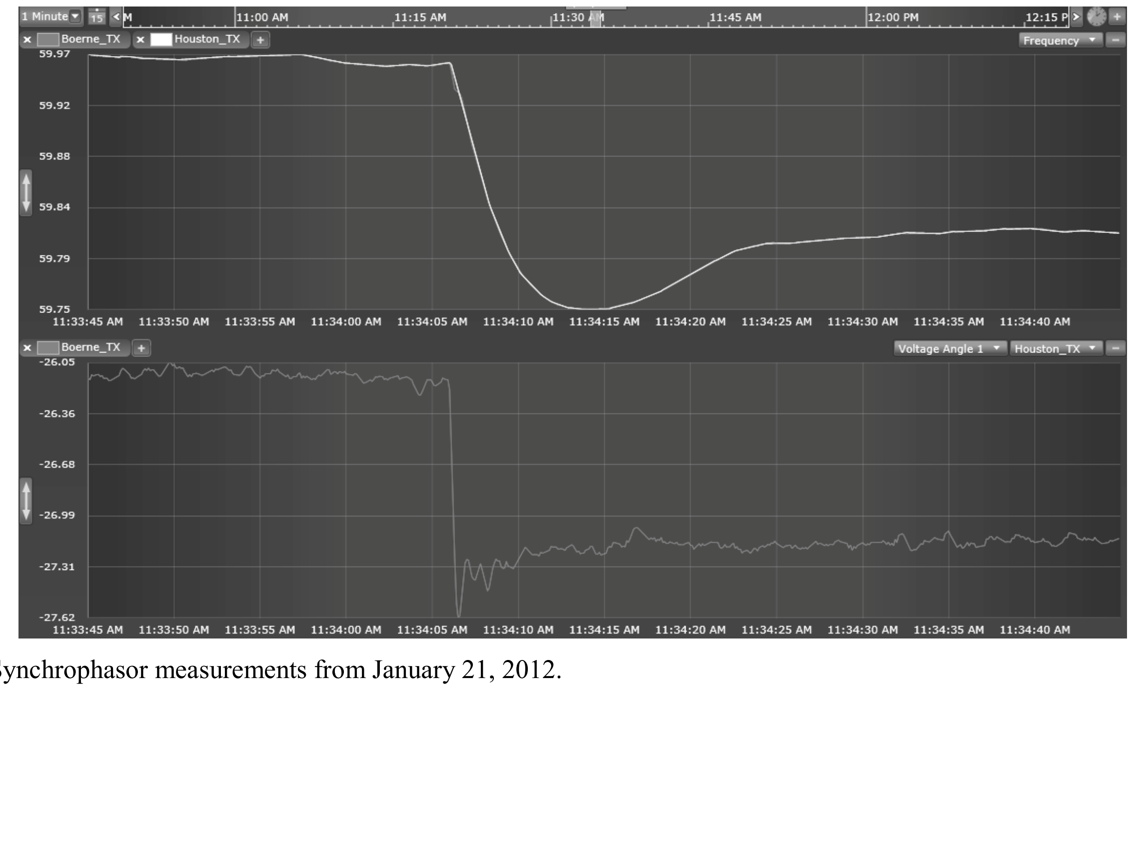

Fig. 2. Synchrophasor measurements from January 21, 2012.

During an event of this duration, the mechanical power does not change significantly. Therefore, the relationship in (5) shows how the electric load change is related to *H*. For a situation where the load power change is known, (5) provides an estimate of the system inertial constant. Conversely, if the system inertial constant is known but an operator is trying to determine how much generation was lost, (5) provides this information. Typical values for *H* are in the range of 3 to 12 seconds [1]. According to public records from ERCOT, the event on January 21 was due to losing 584 MW of generation. Substitution of this change into the right side of (5) gives an inertia estimate of $H = 11.2$ seconds.

The inertial performances of renewable generation sources, such as wind turbines and solar arrays, are different than traditional generation sources. A nuclear power plant or coal-fired power plant is directly connected to the power system through a generator with a large turbine, whereas most renewable generation is electronically connected. Tracking the inertial response of the system as a function of time during the installation of renewables helps operators and planners prepare for new system dynamics. This can also provide data when working with renewable generation owners on interconnection requirements.

Compare the information learned from the synchrophasor measurements with what could be learned from a SCADA system. The scan rate for SCADA is in multiples of seconds. Each vertical division in Fig. 2 spans 5 seconds. Therefore, depending on where the samples fall within that 5-second window, the estimate of df/dt is different, and an accurate measurement of the inertial constant or tripped generation power is not guaranteed.

Fig. 2 also shows the angle difference between two locations in the Texas power system. Angle difference is directly related to power flow through (6), which holds if an equivalent line impedance *X* is appropriate, such as in cases where there are no intermediate loads or generation.

$$P = \frac{V_1 V_2 \cos(D)}{X} \tag{6}$$

The synchrophasor measuring system demonstrated here measures distribution voltages, and therefore, V_1 and V_2 are not known. However, again, in a utility application, these values are known. Equation (6), in combination with a known system configuration, enables estimation of *X*. A more detailed line model is shown in Fig. 3.

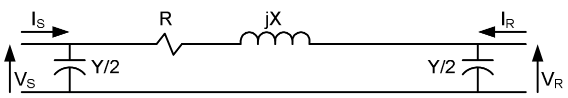

Fig. 3. Transmission line model.

Having time-synchronized current and voltage measurements at both ends of the lines, along with neglecting line resistance *R*, results in two equations, (7) and (8), that are solvable for parameters *X* and *Y* [6]. Using multiple measurements and averaging the results over time can smooth measurement noise and improve the parameter estimate.

$$Z = \frac{\left(V_S^2 - V_R^2\right)}{I_S V_R - I_R V_S} \tag{7}$$

$$Y = 2\frac{\left(I_S + I_R\right)}{V_R + V_S} \tag{8}$$

Another feature of the measurements shown in Fig. 2 is the oscillations in the angle difference values. The ability of synchrophasors to show oscillation behavior is discussed in the next section.

4 Line trip oscillations

The result of a line trip on the frequency of the Western Electricity Coordinating Council (WECC) system is shown in Fig. 4, along with the phase angle between Vancouver, British Columbia, and Vacaville, California. The high-frequency oscillation on the frequency signal is due to local noise sources at the wall outlet location and is not relevant for this discussion.

The signal does exhibit an interesting low-frequency oscillation of the system after losing the line, which is lightly damped. Modal analysis of this response indicates that the oscillation frequency is at 0.4 Hz. The damping ratio of the oscillation is defined by (9).

$$\zeta_m = \frac{-\sigma_m}{\sqrt{\left(\sigma_m^2 + \omega_m^2\right)}} \tag{9}$$

Modal analysis results show that the damping constant is approximately $\sigma_m = -0.2$ seconds^{-1}. Therefore, by (9), the damping ratio is 8 percent. Positive values of damping indicate a decaying oscillation. Analysis of this signal by a utility engineering department can provide information about improving the system to increase the damping ratio. As the penetration of renewable generation sources with associated faster dynamics increases, seeing these oscillations is important.

The horizontal axis scale in Fig. 4 shows 1-second intervals. If a SCADA system were scanning this response every 5 seconds, an important oscillation such as this would be invisible.

Fig. 4 also shows the angle between two locations in the WECC system. Vancouver is toward the northern section of the system, and Vacaville is toward the southern section. Therefore, the angle between these two locations indicates aggregated power flow. Because wall outlet voltages are measured, the specific measured phase is unknown. A rotation by ±120 degrees is possible, and therefore, the absolute value of the phase difference in Fig. 4 does not provide information. However, the relative phase difference shows an oscillation with a peak of approximately 4 degrees and a similar period as the voltage frequency oscillation.

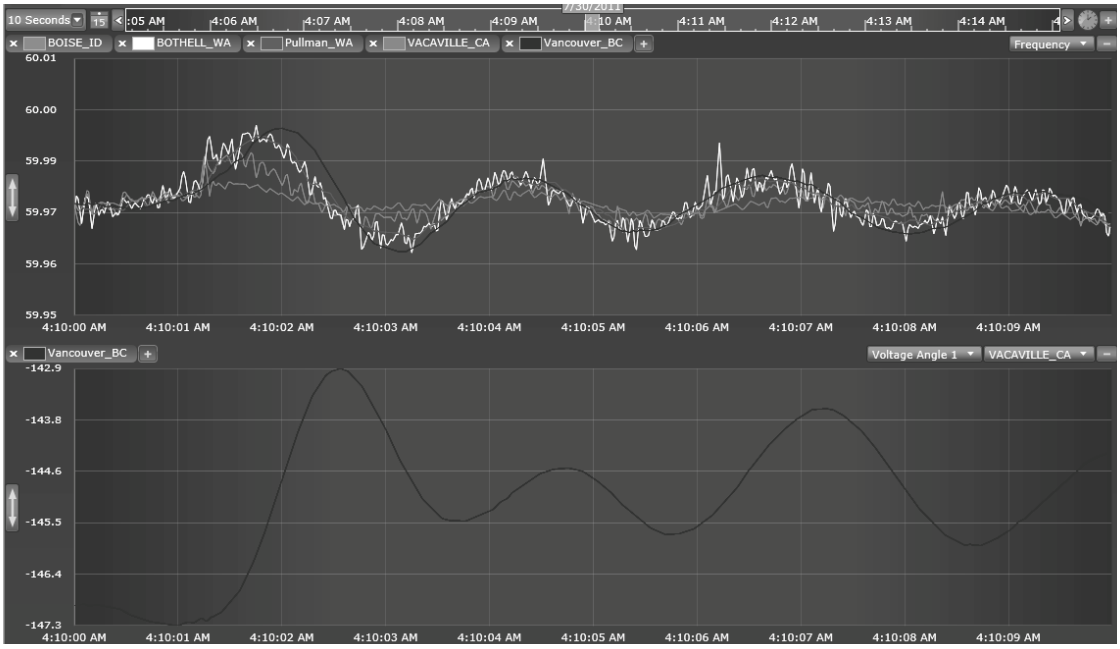

Fig. 4. Line trip event.

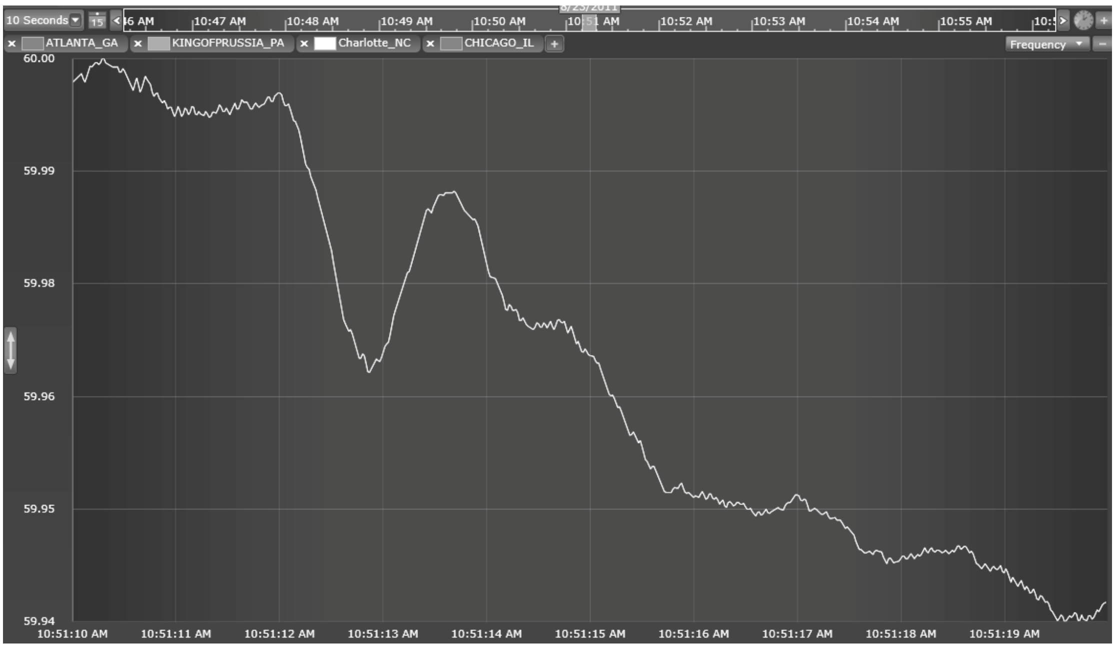

Fig. 5. Frequency at Charlotte, North Carolina.

5 Post-earthquake system response

On August 23, 2011, a 5.8-magnitude earthquake hit the state of Virginia. Ground vibration sensors resulted in the North Anna nuclear generating station tripping offline. This was a loss of approximately 1.8 GW of power. Fig. 5 shows the Eastern Interconnect frequency response immediately after the earthquake.

Unlike the step response of the Texas system in Fig. 2, the frequency after the earthquake exhibits a two-stage drop. Seeing the response in this detail provides information about the sequence of controls during the event. Also, applying (3) to determine the inertial constant must take into account these details of the rate of change of frequency, df/dt. The high synchrophasor sample rate provides the necessary resolution.

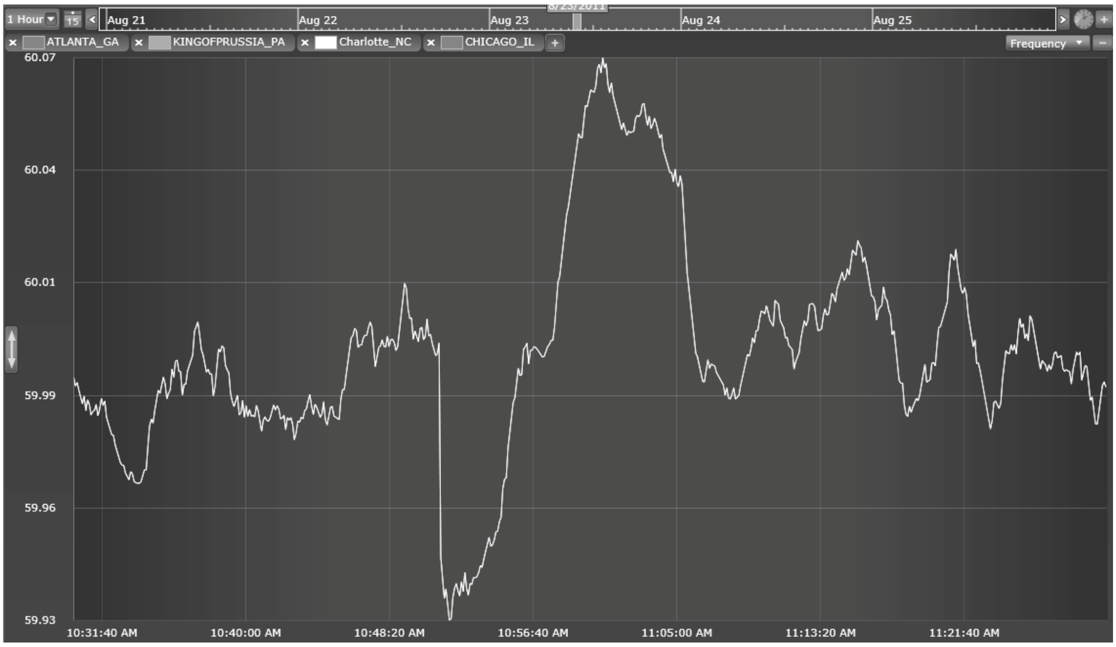

Fig. 6. One-hour range of the system response.

Following the earthquake, loads in the system began to drop out. Fig. 6 shows a 1-hour view, and the effect of load dropping is clearly seen as the frequency rises to 60.07 Hz. Analysis of the frequency increase provides a measure of the amount of load lost in an analogous manner to the description of computing generation lost. Fig. 5 demonstrates the importance of synchrophasor tools that provide multiple time scales for visualization. Operators can use these real-time data to make sure that the system remains in a proper operating region after a major event such as an earthquake.

6 Conclusion

This paper demonstrates the value of synchrophasor measurements for improving system modeling and system operations by analyzing three real power system events. The ability to improve understanding of system parameters and operate the system more effectively is shown.

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