Display and Analysis of Transcontinental Synchrophasors

Roy Moxley, Chuck Petras, Chris Anderson, and Ken Fodero II
Schweitzer Engineering Laboratories, Inc.

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Roy Moxley PE, Chuck Petras PE, Chris Anderson, and Ken Fodero II
Schweitzer Engineering Laboratories, Inc.
Pullman, WA USA

ABSTRACT

This paper details the implementation techniques for a project designed to accomplish four key goals:

1. Send synchrophasor data across a wide-area network (WAN).
2. Align and correlate the data from different sites.
3. Display and update the data in real time to show the relationships between sites.
4. Record the data.

Using some example data, we offer a few observations about how this tool can be useful.

Some of the problems encountered and overcome were different communications latencies from the different locations, loss of communications, excessive network traffic, data buffer overflow, and graphic display for multiple users.

INTRODUCTION

Virtually all commercial electricity generated and used in the developed world is alternating current (ac). While there are a few direct current (dc) connections and transmission lines, the laws of physics and the economics of usage have driven ac networks to dominance. The rise in the 1990s of commercial power plants with long distance power sale contracts increased both the importance of electrical networks and their vulnerability to instabilities.

As an indicator of the state of an electric power system, synchrophasors, or synchronized phasor measurements, must be communicated and time-aligned across the system in order to be valuable. An individual synchrophasor is useful only when compared to other synchrophasors. A comparison provides information about power angles across lines, power transfer, system stability margins, and possible system isolation. Because the stability of power transmission becomes more critical as the transmitted distance increases, synchrophasor data obtained from remote portions of a power network can be very valuable. Displaying synchrophasor data comparisons is a step towards closed loop control—a step that helps improve the security and stability of the overall power system.

North America has five different synchronous networks: Eastern Interconnection, Western Interconnection, ERCOT (Texas), Mexico, and Quebec (see Figure 1). In order to present a view of most of the North American power system, we placed phasor measurement units (PMUs) in Pullman, Washington; Boerne, Texas; Philadelphia, Pennsylvania; and Monterrey, Mexico. We placed additional PMUs in Belleville, Illinois and Tampa, Florida.

Every connected generator in each of the networks is synchronously tied to every other generator in its network, but within a network, generator units that are synchronously tied together are not perfectly in phase. The relative angles between generators change with load flows across the system. The purpose of this project is to develop a low-cost method for displaying—in real time—phase angles relative to each of the networks, without appreciable communications delays.

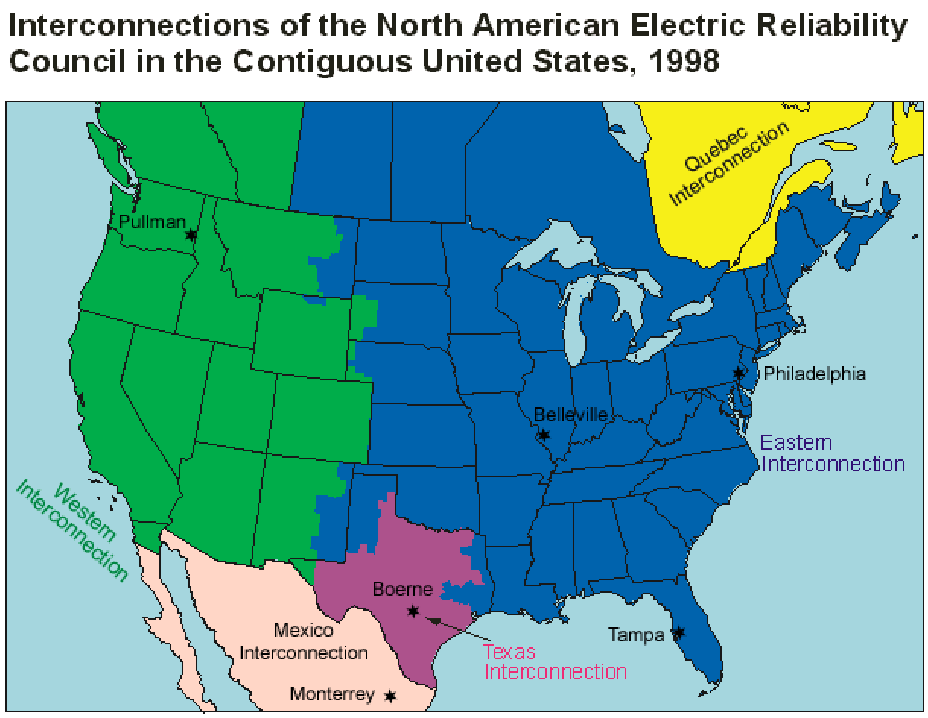

Figure 1 U.S., Canada, and Mexico Electric Networks

* Map courtesy of the North American Electric Reliability Council (NERC).

Sending the Data Across a WAN

The field component of the demonstration is composed of a PMU, a high-accuracy clock (based on a Global Positioning System, or GPS), a voltage source, and some form of data communications (Figure 2).

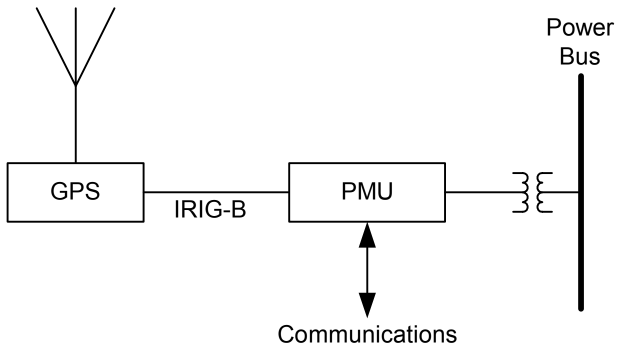

Figure 2 Field Components

Phasor Measurement Equipment

The PMUs are of two different types, but both have the same synchrophasor message format (see Table 1). This message is delivered to an Ethernet or serial port on the device. A setting in each device, PMDATA, defines the analog quantities the device will send in the message. The message size will vary depending on this setting, ranging from 40 to 96 bytes (see Table 1). A new IEEE standard data format is being established that may change the exact message format. The principle of the information and data being transmitted is not significantly changed.

Table 1 Synchrophasor Message Format

PMDATA Setting (see Note 0)			Synchrophasor Unsolicited Write Message	
V1	**V**	**A**	**Data**	**Description**
x	x	x	0xA546	header
x	x	x	0xXX	length (A = 0x60, V = 0x40, V1 = 0x28)
x	x	x	0x0000000000	Routing (UINT40) (must be 0)
x	x	x	0x00	Status Byte (must be 0)
x	x	x	0x20	Function code
x	x	x	0xC0	Sequence byte (0xC0 – single frame message)
x	x	x	0x00	Response Number (always 00)
x	x	x	0xaaaaaaaa	destination address (UINT64) (See Note 1)
x	x	x	0xXXXX	register count (UINT16) (See Note 2)
x	x	x	0xXXXX	sample number (UINT16) (See Note 3)
x	x	x	0xXXXXXXXX	SOC (second of century) (UINT64)
x	x	x	0xffffffff	FREQ_PM (FLOAT32)
	x	x	0xXXXXXXXX	VAM_PM (FLOAT32)
	x	x	0xXXXXXXXX	VAA_PM (FLOAT32)
	x	x	0xXXXXXXXX	VBM_PM (FLOAT32)
	x	x	0xXXXXXXXX	VBA_PM (FLOAT32)
	x	x	0xXXXXXXXX	VCM_PM (FLOAT32)
	x	x	0xXXXXXXXX	VCA_PM (FLOAT32)
x	x	x	0xXXXXXXXX	V1M_PM (FLOAT32)
x	x	x	0xXXXXXXXX	V1A_PM (FLOAT32)
		x	0xXXXXXXXX	IAM_PM (FLOAT32)
		x	0xXXXXXXXX	IAA_PM (FLOAT32)
		x	0xXXXXXXXX	IBM_PM (FLOAT32)
		x	0xXXXXXXXX	IBA_PM (FLOAT32)
		x	0xXXXXXXXX	ICM_PM (FLOAT32)
		x	0xXXXXXXXX	ICA_PM (FLOAT32)
		x	0xXXXXXXXX	I1M_PM (FLOAT32)
		x	0xXXXXXXXX	I1A_PM (FLOAT32)
x	x	x	0xXXXX	Status Word (UINT16) (See Note 4)
x	x	x	0xYYYY	CRC-16 checkcode for message (UINT16)

NOTES:

0 – PMU settings to determine message content.

1 – Destination address uses address from setting PMADDR.

2 – Register count (number of 2-byte data values, including sample number, SOC, frequency, analogs and digital data. Does not include checksum). This value is number of bytes of data divided by two.

3 – Sample number zero-based 50 millisecond index into SOC of this packet (i.e., if packets are being transmitted every 500 ms, the index is 0 and 10). Index is in 50 millisecond increments.

4 – TSOK, PMDOK, and xxnn-xxmm bits (TSOK is in LSB, xxmm is in MSB).

GPS Clock Source

The PMUs used in this demonstration required a synchronized signal accurate to within ±500 ns of Universal Time Coordination (UTC). This is available in most GPS-based clocks.

Voltage Source

For all of the PMUs, the voltage source is a 115 Vac wall socket at the location selected, connected to the A-phase input of the PMU. Transmission bus voltage would be used in a control application, removing any ambiguity caused by unknown power system phases and phase shifts caused by power transformers. In addition, because only one phase was available, the positive-sequence values have no meaning in this application.

Data Communications

For communications over a WAN, serial data are converted to Ethernet using an Ethernet transceiver (in the case of serial-only PMUs), or directly connected to the Ethernet (for Ethernet native devices). The Ethernet data are then sent via TCP/IP over a WAN with several different communications media. All of the WAN connections previously existed and are primarily used for business communications.

From Monterrey, Mexico, communication is over a Virtual Private Network (VPN) connection using the Internet. This provides an economical connection with good security. The connections from Texas, Illinois, and Florida use frame relay technology over leased phone lines. The Pennsylvania connection is a dedicated T1 line.

The system concept and its network connections are shown in Figure 3; the phasor data concentrator (PDC) and the PMUs are behind a firewall for security against unauthorized access.

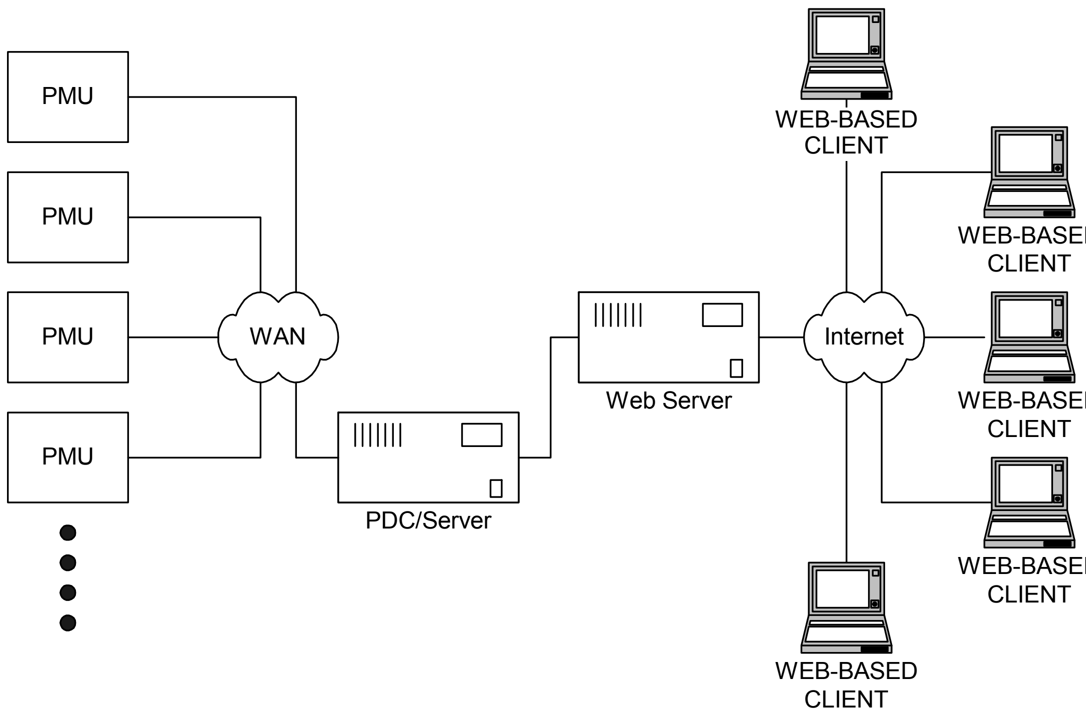

Figure 3 Network Configuration

ALIGNING AND CORRELATING THE DATA FROM DIFFERENT SITES

The overall software system architecture consists of a Perl script and two Java applets (see Figure 4).

Perl is a high-level programming language well suited for tasks involving system utilities, software tools, system management tasks, database access, graphical programming, networking, and world-wide web programming, among other applications [1]. For this project, a Perl script moves data from the PDC to a web server.

An applet is a program written in the Java programming language and embedded within a web page. Where a typical web page usually renders text and images for the viewer, an applet provides greater functionality to the web page because it is an application. An applet file is downloaded along with the web page, and runs from within the client’s web browser. For this demonstration, the applets collect data from the web server, calculate phase angles, and render a graphical representation of phasors.

Phasor Data Concentrator

Because the goal of this project is to send and display data in real time, a software-based PDC is used. The PDC is a program written in C that resides in a dedicated server. The PDC connects to all of the PMUs using TCP/IP Telnet connections over their respective Ethernet connections. These are established using TCP/IP sockets. The PDC takes synchrophasor data from the PMUs and buffers it for access by the Perl script running in the web server.

For the purpose of post-disturbance analysis, another option would be to record data over a long period of time, in which case a database should be used instead of a PDC. This is advantageous because recent network events have demonstrated that anomalies indicating power system instability can occur days before the instability becomes critical. However, the amount of data and the transmit rate will have a significant impact on data storage requirements. Table 2 shows how much data each PMU generates, depending on the PMDATA setting (see Table 1). This is an important consideration when researching a wide-area measurement application.

Table 2 Aggregate Data Transmitted per PMU

PMDATA = A	Bytes		
# Msg/Sec	Per Sec	Per Day	Per Week
1	96	8,294,400	58,060,800
5	480	41,472,000	290,304,000
10	960	82,944,000	580,608,000
20	1920	165,888,000	1,161,216,000

Time Synchronization in the PDC

The time alignment of the incoming synchrophasor data is critical to the usefulness of the results. Because phase angles shift with time, an error in time alignment will translate to an error in phase angle. Each message includes a time stamp that uses the second of century (SOC) for a unique message label, and a message number (which further subdivides the SOC). For this project, each PMU sends 10 messages per second. At data reception, the PDC aligns each message using the SOC and message number in a ten-second ring buffer (see Figure 4). The buffer consists of 10 slots, each storing 1 second of data from all of the PMUs.

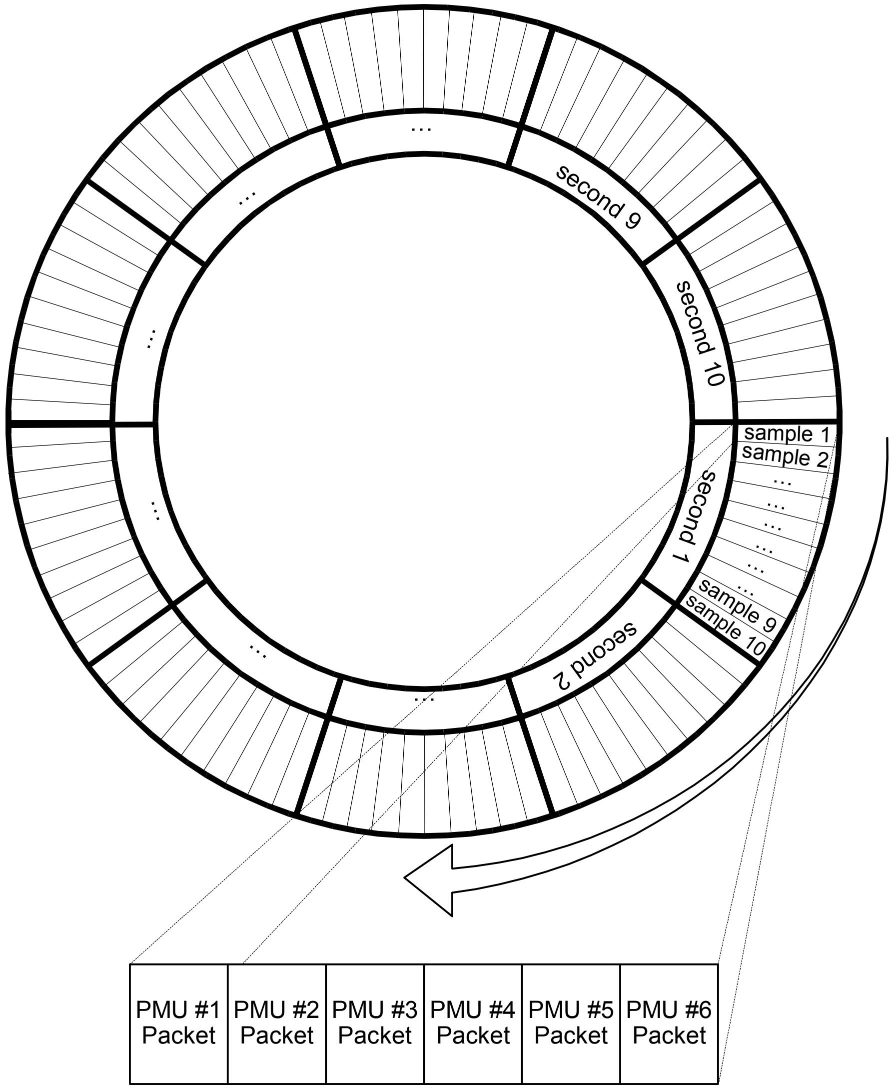

Figure 4 Time Alignment Ring Buffer

Perl Script

Security considerations make it impossible for a Java applet to directly communicate with the PDC. To overcome this limitation, the web server runs a Perl script that periodically polls the PDC using User Datagram Protocol (UDP); the script writes a pair of data files to the web server. These files form the basis for getting the synchrophasor data to the Java applets.

Another function of the Perl script is to analyze the packets sent by the concentrator, then choose the oldest data set, within the buffer period, that includes responses from the most PMUs. This method ensures that only the most complete data are provided. In this demonstration system, the goal is to display real-time streaming data, with minimal latency. However, if the information were used in an offline recording system or analysis program, then it would be feasible to conserve all of the received data for thorough post-disturbance analysis.

A one-second refresh rate is used for demonstration purposes, between the Java applet and the web server, and helps to minimize Internet communications traffic.

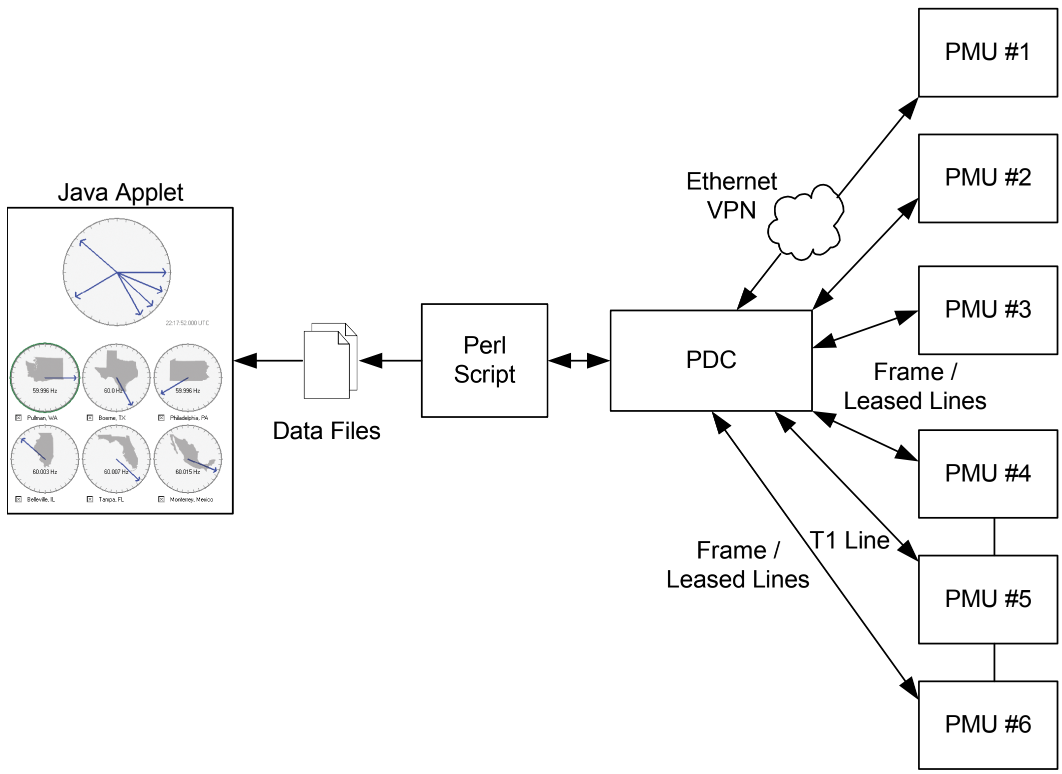

Figure 5 System Architecture

Java Applets Display Instantaneous Phase Angle and Frequency

When a client PC accesses the web page, the Java applet is loaded from the server. When the Java applet is launched in a web browser, it reads the data file that contains the list of PMUs connected to the PDC. Table 3 shows the message format for the applet input data format.

One applet uses these data to configure the display to show phasor plots for each PMU connected to the PDC (Figure 6), while another applet starts a ten-minute rolling display of frequency (Figure 8 and Figure 9). Both applets read the file on the web server containing the synchrophasor data, and display the resulting information on the user's screen every second.

Table 3 Applet Input Data Format

```
>> The file meterdata1.dat is binary and has the following format:
>>
>> A7    Message Header Byte
>> 25    Message Header Byte
>> 01    Function code
>> XX    Length Byte (Total number of bytes)
>> XX    Number of Relays/Meters
>> XX    Message Rate
>> 20    Bytes - Relay/Meter Name (Null Terminated)
>>
>> The Relay/Meter name portion of the message is repeated for "Number of
>> Relays/Meters" times.
>>
```

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```
>> The file meterdata2.dat is binary and has the following format:
>>
>> A7    Message Header Byte
>> 25    Message Header Byte
>> 02    Data Message Function Code
>> XX    Length Byte (Total number of bytes)
>> XX    Hours
>> XX    Minutes
>> XX    Seconds
>> XX    Sample number
>> 4 Bytes     Angle (IEEE Float)
>> 4 Bytes     Frequency (IEEE Float)
>> 4 Bytes     Magnitude (IEEE Float)
>> XX    Clock Good (= 1)
>> XX    Message Good (= 1)
>>
>> The portion of the message from Angle to Message Good repeats N times,
>> where N is the "Number of Relays/Meters" that data are being received from.
```

DISPLAYING AND UPDATING THE DATA IN REAL TIME

The display of instantaneous phase angle (Figure 6) is one of the most basic ways of displaying synchrophasor information. With one of the units set as the "reference" location, all other units have their phase angle displayed as a difference from that location. In order to display relative phase angle, a large "dial" was added to show selected phasors. This can show all of the phasors or a selected subset of phasors from the same or different networks. For details on how the measured voltage angles are established, see Reference [2] or the appendix at the end of this paper.

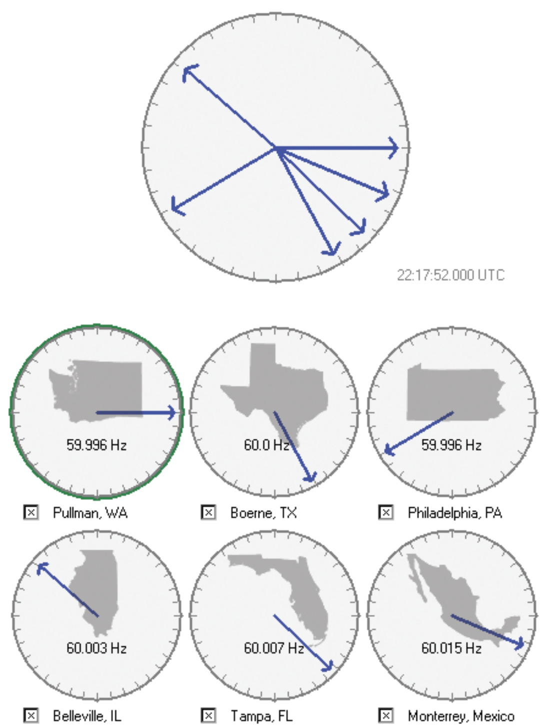

Figure 6 Screen Display of Synchrophasor Data

RECORDING THE DATA

Once the real-time phase angle and frequency were displayed, the next step was to implement a display of trends in frequency. Though any power system variable (e.g., magnitude, phase angle) can be used for this type of display, for this demonstration we chose frequency. Monitoring frequency is useful for examining natural resonant oscillations of the power system, looking at damping of disturbances, or just checking for frequency stability over time in a large area.

The limits of using a computer display screen made certain selections about the application necessary. For example, a ten-minute window is best for this web applet. The reason for this is that each bar (sample) in the graph is one pixel wide, and 600 pixels were allocated for the graph width. This mandates that 600 seconds of data be displayed (see Figure 7).

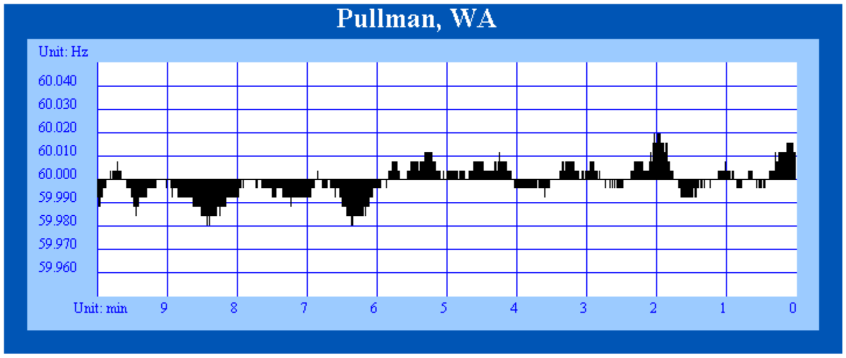

Figure 7 Frequency Display

Observations

Viewing the main three North American networks (Figure 8) in the frequency domain quickly reveals several interesting characteristics and phenomena that can also apply to smaller areas. First, a visual display of $\int dfdt$ shows clearly that the three areas—Pullman, Boerne, and Philadelphia—are disconnected from each other. Of course, a system map could reveal the same thing in this case, but in a system where connections are dependent on switch or circuit breaker position, the frequency display makes a system separation very obvious.

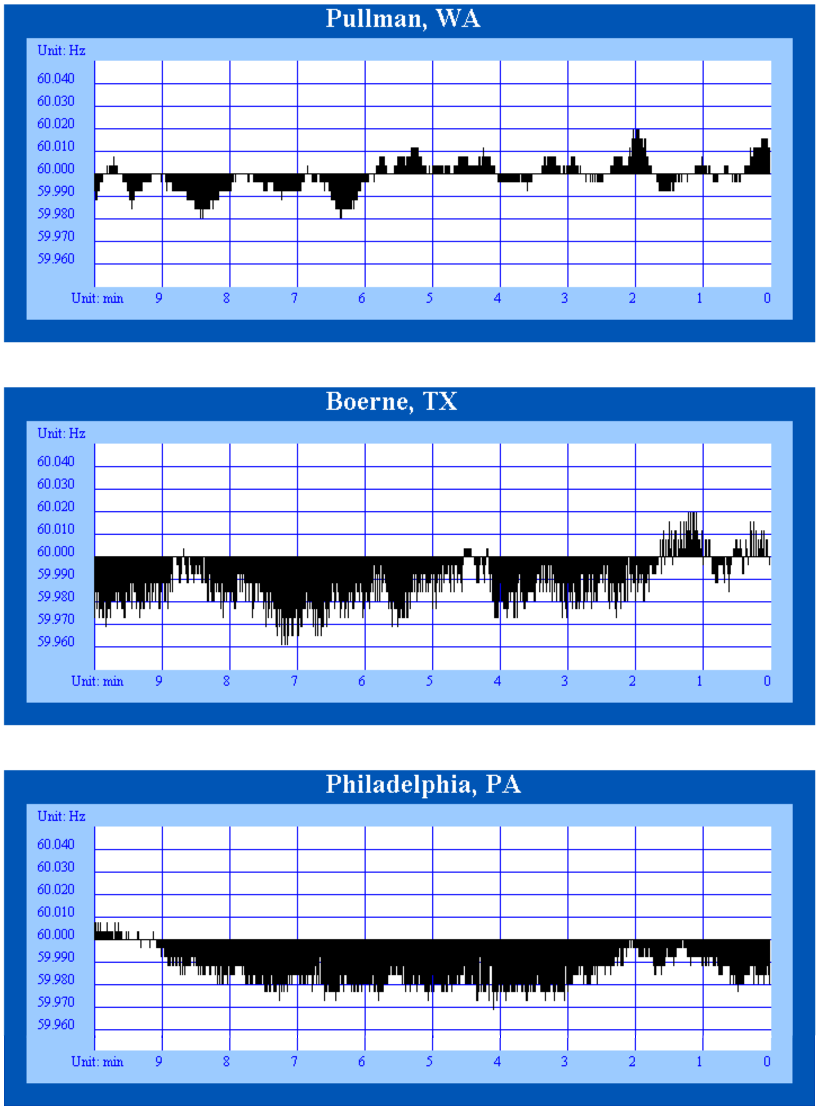

Figure 8 Screen Display of Frequency Profile for Three North American Networks

The next characteristic of the different systems is their different time constants, which is easily seen in the display of Figure 8. The frequency in the West seems to have a very short time response to control, Texas has a longer time constant, and the Eastern interconnection is longer still. In general, the longer time constant is indicative of greater stability [4] [5]. Other possibilities include different control settings. Analyzing trends in frequency time constants at different locations provides additional insight and opportunities for study into the stability of the power system.

Looking at three displays from the same network (Figure 9) also offers insight into the possibilities of analysis based on synchrophasor data. The most obvious item here is the lost packets of data from the Belleville PMU. This was determined to be a data-handling problem and was later corrected.

Looking at the basic data in Figure 9, as opposed to the data in Figure 8, we can see that these three locations are interconnected. The deviation between samples in Philadelphia and Tampa is interesting. Because of the higher instantaneous changes in frequency between samples, although still small, it can be surmised that the particular feeder network providing power to the Philadelphia PMU is a much stronger source than that feeding the Tampa PMU. It also demonstrates the difficulties of using a “Rate of Change of Frequency” device without significant filtering.

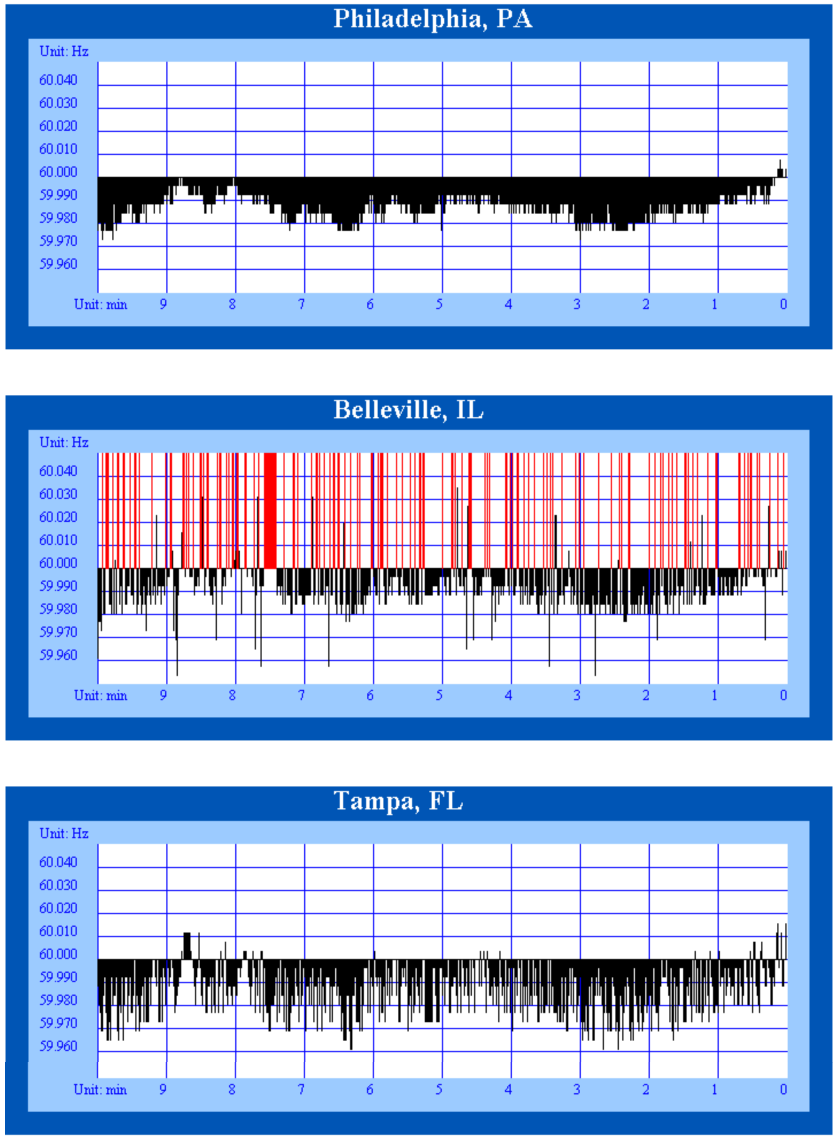

Figure 9 Screen Display of Three Locations on the Eastern Network

CONQUERING IMPLEMENTATION OBSTACLES

Most of the problems in producing this wide-area display were in making the transition from the website to the display—the function of the Java applet. Debugging the Java applet was difficult because of its interaction with the data files. It was necessary to upload a new file each time, and then test it. Several iterations were required to keep the display online through data “dropouts” caused by communications delays or loss of the satellite clock signal at the remote locations. Some items that would seem to be easy to modify turned out to be quite difficult. For example, it would be easier to compare phasor angles in the large display if each vector were color coded by location. However, this would add significant work, requiring complete re-creation of the display code for each PMU.

It should be noted that in terms of manpower this was not an extensive project. One undergraduate electrical engineering intern coded the PDC and Perl script in three months, with intermittent assistance from a few engineers and the corporate webmaster. The same intern coded the phase-angle-display during the same time frame. A second intern coded the frequency-trending display in five days, using the same Java applet data feeds (Table 2).

CONCLUSIONS

In this paper, we do not attempt to draw any power system conclusions from the information derived from the wide-area measurements themselves; instead we are focusing on what was learned by the exercise of collecting, displaying, and recording the data.

1. Because of communications latencies, it was difficult to obtain a real-time display without buffering. Using multiple path types (VPN, frame relay, T1) complicated the buffering and necessitated the relatively long delay. If display or control applications required a shorter time delay, it would require more work on either making the communications from each site consistent with all other sites, or designing the display or control algorithm to accommodate dropped data points.
2. The biggest obstacle we faced in adding sites was getting a satellite clock signal into the offices where most of the PMUs were located. Because the communications bandwidth required was low compared to business requirements, the data transmission task was fairly easy. The PMUs all had the same output data format, which meant that the PDC scaling required almost no additional work.
3. Enhancing the functionality of the synchrophasor display with additional capability takes very little work once the basic hardware and software is in place. Going from concept to online for the initial synchrophasor display took three months of calendar time. Adding the frequency trending report took an additional five days.

FUTURE DEVELOPMENTS

1. Display is one step toward automatic control. Simple algorithms should be developed for alarms based on conditions such as islanding, undamped, or negatively damped system oscillation, or unacceptably large power angles across selected segments of a power system.
2. Recording synchrophasor data for event analysis could be considered as important for system-wide events as fault current recording is important for line or station faults.
3. As PMUs are available in greater quantities across a power system, opportunities for advanced applications grow. Making provision for communication of synchrophasor information to a control center should be considered as important as knowing breaker status. Both pieces of data are valuable in making critical control decisions.

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BIOGRAPHIES

Roy Moxley has a B.S. in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories in 2000 as market manager for Transmission System Products. Prior to that he was with General Electric Company as a relay application engineer, Transmission and Distribution (T&D) field application engineer, and T&D account manager. He is a registered professional engineer in Pennsylvania.

Chuck Petras has a Bachelor of Electrical Engineering (B.E.E.) degree from Cleveland State University. He joined Schweitzer Engineering Laboratories in 2000 and is a research engineer. He is a registered professional engineer in Oregon.

Chris Anderson has an A.A.S in Electronics Engineering Technology from I.T.T. Technical Institute, and is currently working on his B.S. in Electrical Engineering through Kennedy Western University. He joined SEL in July 1999. In the first three years at SEL, he worked in product development for transmission protection products. Since 2002, he has been an associate product engineer supporting transmission protection in Research and Development.

Kenneth Fodero II is currently an undergraduate student working towards his B.S. in Electrical Engineering at the University of Washington. He has worked at Schweitzer Engineering Laboratories over two summer internships. During the most recent internship, he worked as a research engineering intern.

APPENDIX

Building a Synchrophasor

Because it is well known that there must be latencies communicating information between any two points, there must be a system of defining the angle of a waveform at a given instant. Defining relative waveforms at different locations starts with defining a reference wave based only on a satellite clock reference.

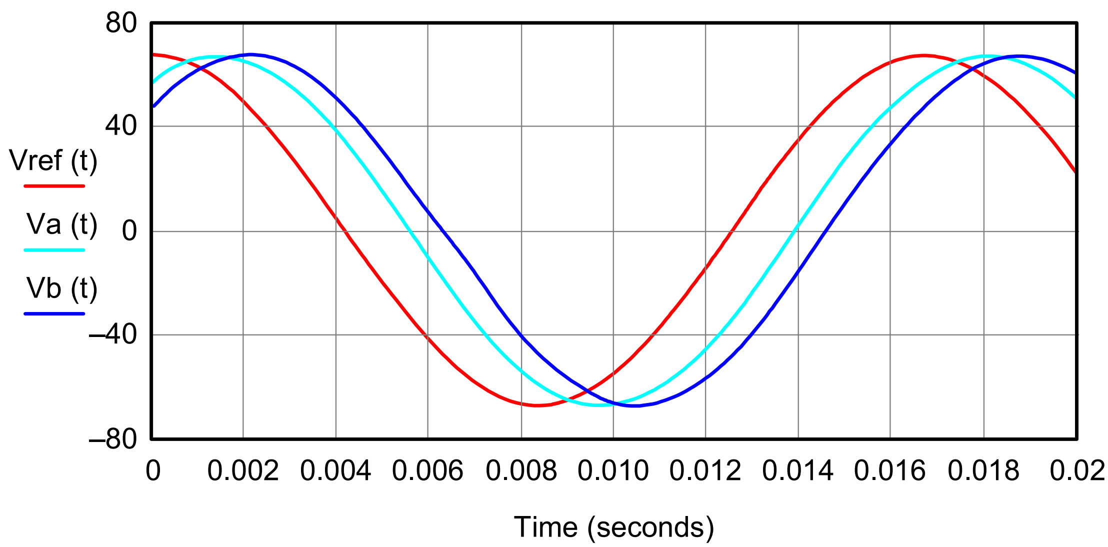

Figure 10 Angle Reference Measurement

As shown in Figure 10, the reference waveform has a peak value of t = 0 seconds. Using a high-accuracy satellite clock reference to define this wave can provide enough accuracy for the measured values to be sufficient for analysis. For example, an accuracy of ±10 microseconds between measured waves would provide for an angular accuracy of ±0.22 electrical degrees at 60 Hertz (10µ seconds / .0167 seconds per cycle • 360 degrees per cycle). The key of comparative synchrophasor measurements at different locations is to have exactly the same reference wave created at each of these locations.

With an identical reference waveform at multiple locations, each PMU can now measure the magnitude and relative phase angle of a voltage or current. That magnitude and phase angle, coupled with the exact time of the measurement, is referred to as a synchrophasor.

Reference [2] gives a derivation for comparing phasor measurements between locations that may or may not be connected. Measuring voltage as a function of time at any point on the system, we can use the following equation:

$$V(t) = V \bullet \cos(2 \bullet \pi \bullet f \bullet t + \phi) \tag{1}$$

Breaking out the angular portion of the equation, we have:

$$\theta(t) = 2 \bullet \pi \bullet f \bullet t + \phi \tag{2}$$

To make this equation more general, we add a term for off nominal frequency, where:

$$\Delta f = f - f_{nom}$$

this gives us the general equation:

$$\theta(t) = 2 \bullet \pi \bullet f_{nom} \bullet t + 2 \bullet \pi \bullet \Delta f \bullet t + \phi \quad (3)$$

Because all locations within an operating region have the same nominal frequency, we can remove the first part of the equation and have only a term relating to both phase shift and off nominal frequency operation:

$$\beta(t) = 2 \bullet \pi \bullet \Delta f \bullet t + \phi$$

We focus on the value, β, to transmit and display from multiple locations within the North American electrical system. Even though the PMUs used at all locations can provide data on the phase voltage and current; positive-sequence voltage and current; and frequency; the only information used for this demonstration was the A-phase voltage.