Synchrophasors in the Real World

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INTRODUCTION

Synchronized phasor measurements, or synchrophasors, provide a method for comparing phase and sequence values from anywhere on a power system. The method of collecting and using this information impacts communications and data processing requirements. These requirements can vary from a serial cable and hand-held calculator to a 1 Gbps Ethernet network with multi-tiered data concentrators and server. This paper details actual and possible applications and describes communication and processing already in place or necessary for a particular application.

Model Validation. Validation of system models and components has been one of the first uses of synchrophasors. This validation occurs through use of inter-area communication or simultaneous data collection of conditions at a single point in time. This paper discusses methods for this type of data collection and provides some of the model equations in use.

Post-Event Analysis. Because data can be archived locally, post-event analysis has been an early application of synchrophasors without wide-area communication. This paper provides examples of system events analyzed through use of synchrophasors and discusses associated data storage requirements.

Real-Time Display, State Measurement. New IEEE standards (PC37.118) standardize data transmission format and sampling rates. This paper discusses communications requirements for different applications.

Real-Time Control. Communication of synchrophasor data across a system can improve stability while reducing costs by improving control capabilities of present wide area control applications. This paper provides example applications with corresponding communications and processing requirements for these and future advanced applications.

Synchrophasors are a powerful control and analysis tool that provides a new view of power systems. Use of this tool will change and improve power delivery automation capabilities after challenges of new data communication requirements are first resolved.

Summary. Synchrophasors provide a display and analysis tool for engineers and operators. Communication and data processing are an integral part of this tool.

Despite offering the promise of optimal power system control, synchrophasors at their heart require the communication of information from widely separated parts of that power system. It is often the case that the degree to which synchrophasors can be made useful to any particular group within an electric utility organization depends on how far and how fast synchrophasor data can be moved from a variety of different locations to where the information can be processed, displayed, and analyzed [1]. Because synchrophasor data are available from a variety of phasor measurement units (PMUs) scattered throughout the power system, it may very well be that this data movement, more than data availability, determines what can be done with this new view of the power system.

WHAT IS A SYNCHROPHASOR?

Synchrophasors, or synchronized phasor measurements, provide a means for comparing a phasor to an absolute time reference. This is similar to putting a timing mark on a virtual generator shaft anywhere on the system and connecting a strobe light source to a single reference point for the entire system. The availability of high-accuracy satellite-synchronized clocks makes synchronized phasor measurement possible. Through the use of the clock, the phasor measurement unit (PMU) produces a reference sinusoidal wave. This reference wave is a nominal frequency sinusoidal wave for which maximum occurs at the exact start of each second. The measured local voltage or current is then compared to this reference wave, as shown in Figure 1 below.

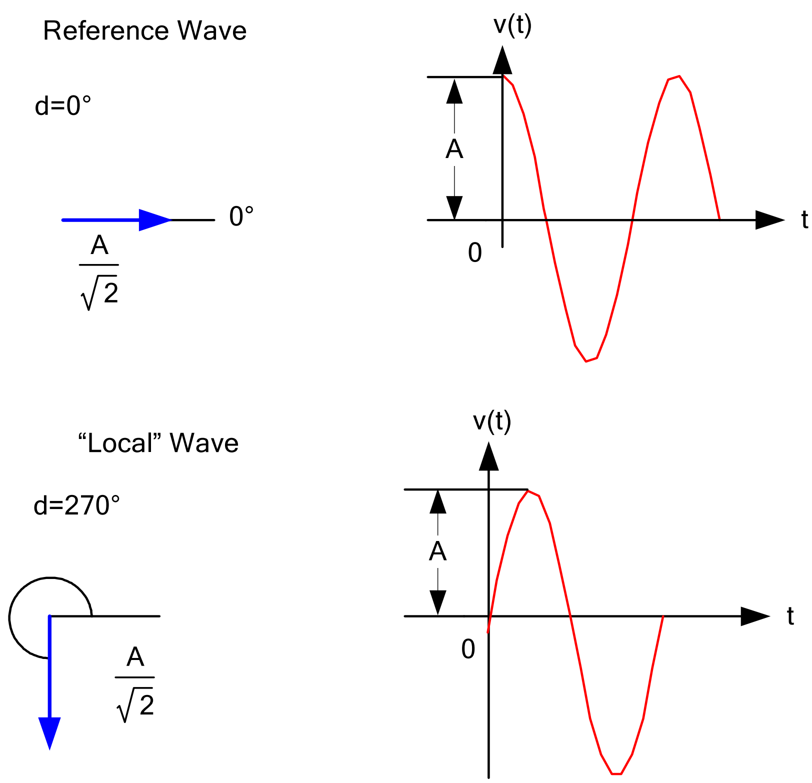

Figure 1 Reference Wave and "Local" Wave With Angular Comparison

Because the reference wave is only dependent on a GPS-generated time signal, this wave will be the same at all different PMU locations. Therefore, a local phasor can be compared with a phasor at any other location, and the angular difference between the two phasors represents the absolute difference between the two locations. Now that this value is available from devices on the power system, the remaining questions are how to make it available to application programs, and how system personnel are to use this value.

MODEL VALIDATION

Power flows, voltages, and currents respond only to the laws of physics. Operators rely on system models to know how those power flows will change either as a result of manual or relay-initiated changes to topology. Such changes could include line tripping, capacitor bank insertion, or generator starting. All of these actions can increase or decrease the total cost of power delivered to customers. An action that might be desirable from an economic standpoint, such as importing more economical power over a transmission line, can be undesirable from a security standpoint, such as the loading of the transmission line over a stability limit. Model accuracy can help ensure economic optimization of system assets.

A simple case of model validation, or model creation, is determining the impedance of a single transmission line. Consider a single transmission line such as in Figure 2.

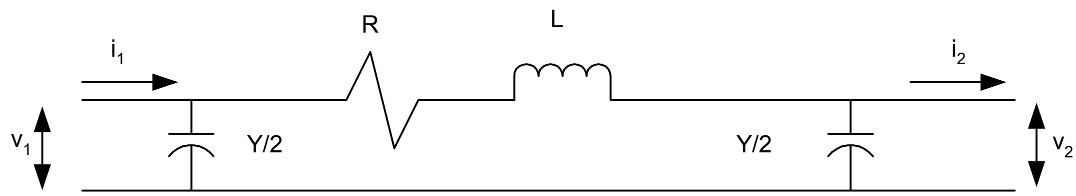

Figure 2 Simple Model of a Transmission Line

In this case, we observe the current and voltage at each end of the line and write the equations to solve for the line constants:

$$i_1 = v_1 \bullet Y/2 + (v_1 - v_2)/Z$$

where $Z = R + j\omega L$

and

$$i_2 = (v_1 - v_2) / Z - v_2 \bullet Y/2$$

We can then solve for the line constants with the following equations:

$$Y = \frac{i_1 - i_2}{v_1 + v_2} \bullet 2$$

$$C = \mathrm{Im}(Y) / 2\pi f$$

and

$$Z = \frac{v_1{}^2 - v_2{}^2}{i_1 v_2 + i_2 v_1}$$

$$R = \mathrm{Re}(Z)$$

$$L = \mathrm{Im}(Z) / 2\pi f$$

All of these equations existed before synchrophasors. It seems that all the variables in the equations are available without the need for satellite clocks, but these equations fail to incorporate an important detail: the voltages and currents must be measured at the same point in time for the equations to be valid.

What type of communication is necessary to ensure the simultaneity of this measurement? The answer is, that while a channel from the two line ends to a computer is convenient, no high-speed communication is necessary. The important thing is that the measurement must be taken at exactly the same instant in time, not that the solution to the equations be done at that instant. A user can have two PMUs, one at each end of the line, and issue commands to provide the voltages and currents at the same time. Communication can be by Ethernet, phone modem, or just an EIA-232 cable from the PMU to a computer at each end of the line.

MODEL LIMITATIONS

Operators and planners must base their decisions on system models. The "quality" of operation or planning decisions is directly impacted by the quality of the model. No model is perfect, but the accuracy of the model does limit how the model can be used. Consider the diagram in Figure 3 [2].

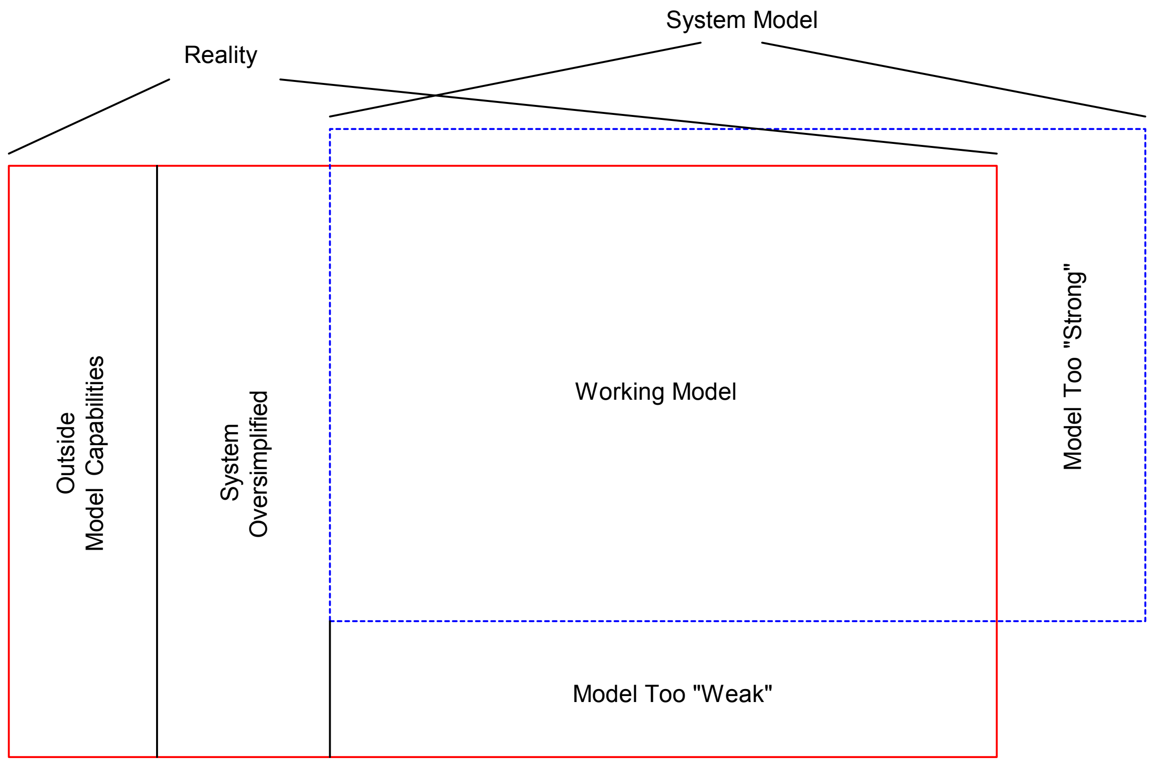

Figure 3 Limitations of a System Model

To the extent that the model is not a perfect representation of "reality," an operator who bases control action on the model will either go beyond the system capabilities or fail to optimize system capabilities. By providing a margin, one can avoid the consequences of operating beyond the boundaries of safety, or those defined by "Reality." Because this margin must keep the operator inside the safe region, there will be unused capability. The objective of state estimation programs is to provide a model of the system to operators that is as close to reality as possible without going beyond system capabilities into an unstable operating condition. Consider an example system containing 9 buses and 14 lines, as shown in Figure 4.

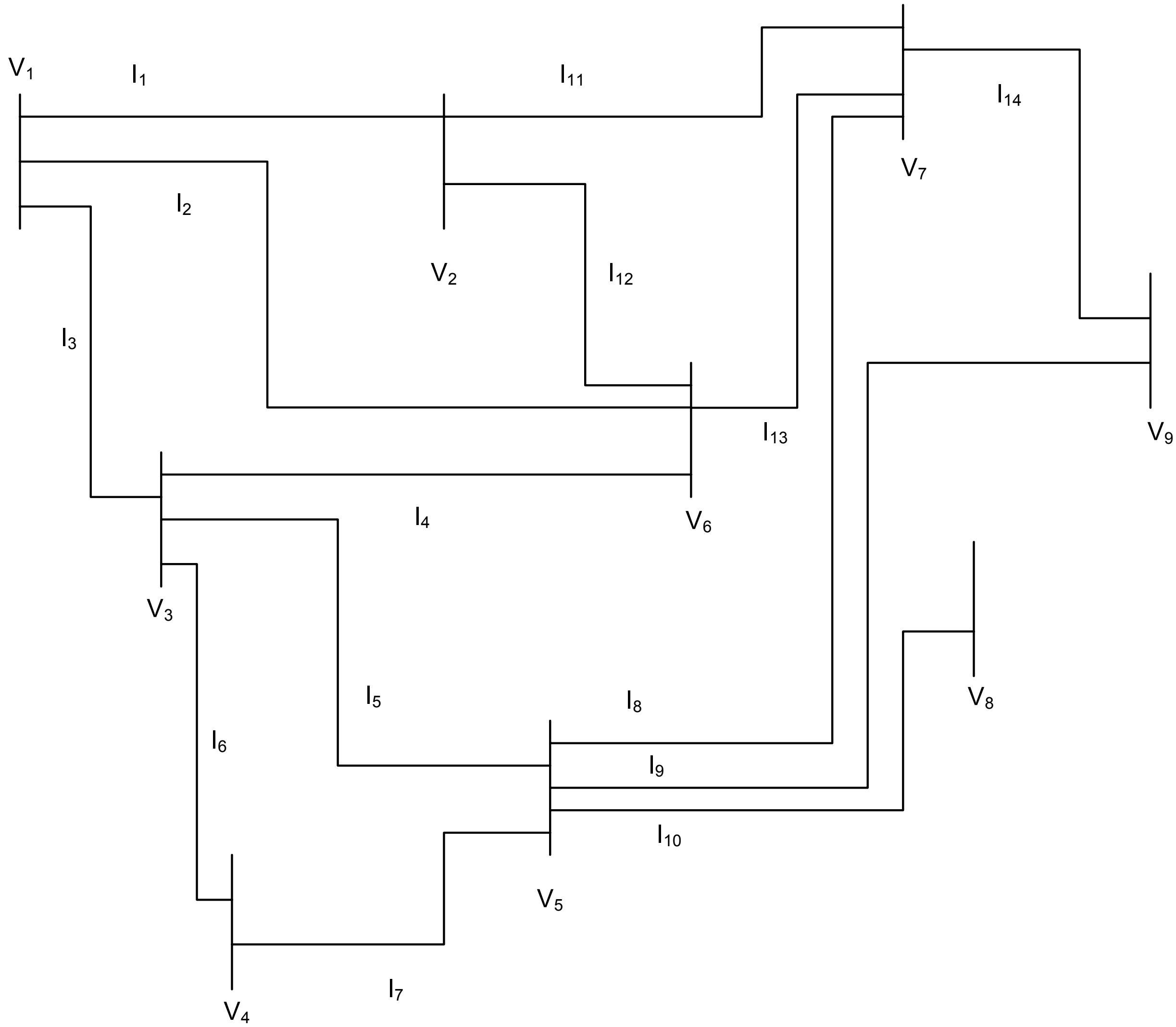

Figure 4 Example System for State Measurement Requirements

To determine the system state, we do not need to measure every voltage and current on the system [3]. By measuring the voltages and currents at the proper locations, we can obtain sufficient information to describe the system state; we do not need to measure every line and bus directly. In this case, we can obtain a "depth of observability" of no more than one, by measuring the voltages and currents at only two locations. In other words, we will be no more than one bus away from a measured voltage, and we will have a measured current connecting from a known voltage to every other bus on the system, as shown in

Figure 5.

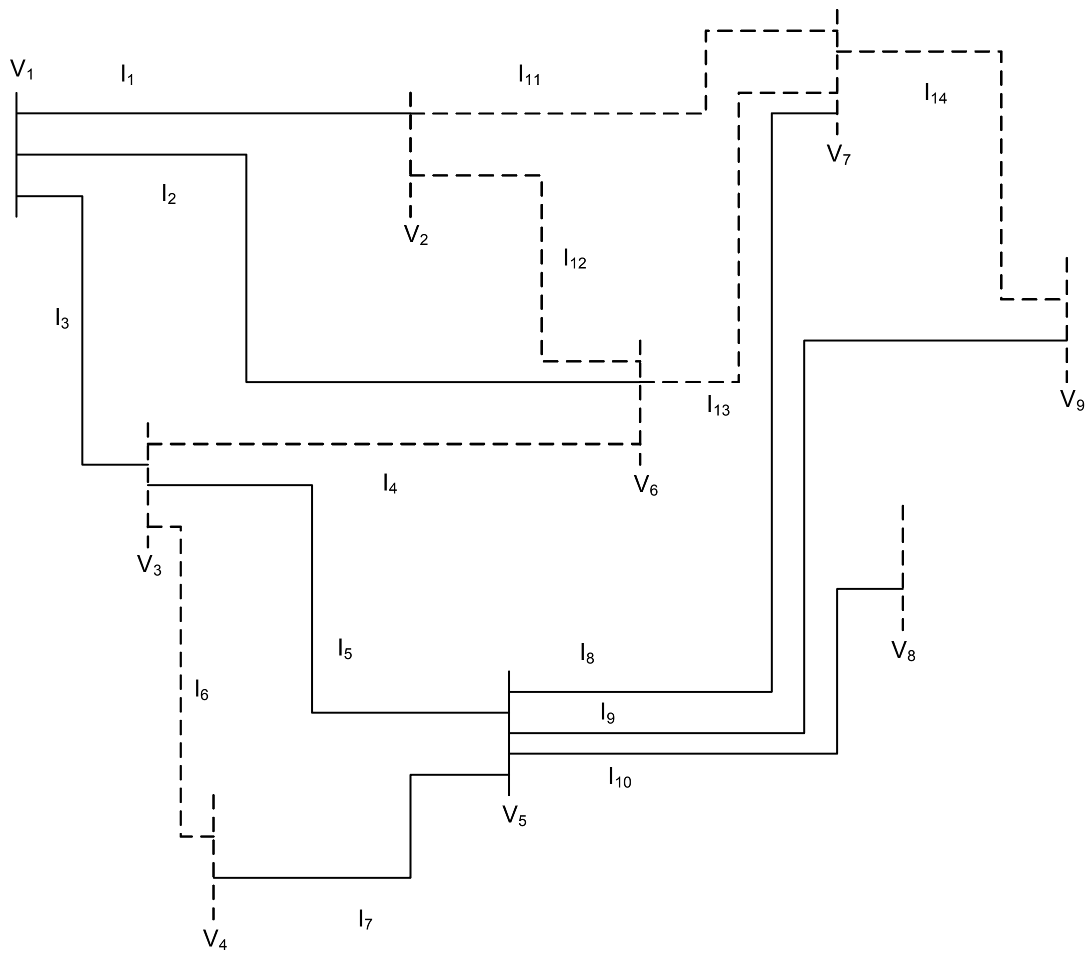

Figure 5 Observation of System From Two Locations

The number of system observation points necessary to determine the state of the system relates directly to the establishment of communications requirements. In practice, the availability of communication may determine which buses one chooses as the basis for observations. A bus in an optimal location may be unsuitable because it fails to optimize the available communications bandwidth. The selection of locations for a phasor data concentrator will be a result of an analysis of where one can achieve “the most bang for the buck.”

One problem that arises is how deep into a system a model needs to go. In the case of the August 14, 2003 blackout in the Northeastern United States, prevailing thought is that the initiating events began with the tripping of 345 kV bulk transmission lines [4]. After the tripping of these lines, a number of 138 kV lines began to trip on overload. This tripping sequence of more than 20 minutes and the ensuing cascading blackout have been attributed to a “lack of situational awareness” on the part of operators. In this case, looking only at the 345 kV system would not have given a complete picture of what was happening.

BASIC COMMUNICATIONS BANDWIDTH REQUIREMENTS

Either before or as part of establishing locations from which to observe the power system, one should determine the amount of communications bandwidth necessary. There are several options for the amount of phasor information sent in the synchrophasor message. As a minimum, one should send the positive-sequence voltage. Because of the need for timestamp and status information, this transmission will require a data packet size of 208 bits or 26 bytes if sent in IEEE PC37.118 16 bit integer format. This format standard also includes frequency and rate of change of frequency in each message. Once the frequency and size of the messages are known, use the following equation to determine the rate at which the data can be sent [5]:

$$\text{bps} = 1.2\left(\text{nn} \bullet \text{L} \bullet \text{f}\right)$$

where:

nn = message size (bytes)
L = length of message byte (1 start bit, 8 data bits, 2 stop bits, 1 parity = 12)
f = frequency of messages
1.2 = factor to account for system delays (based on typical experience)

If you send the data over an Ethernet channel, the transmission packet size will be about twice as large to provide overhead and “envelope” information. All references in this paper assume a serial channel unless stated otherwise.

The synchrophasor data can be sent at various rates, depending on application requirements. The bandwidth requirements for these different rates are shown in Table 1.

Table 1 Communications Rates for V1 Synchrophasor Information (16-bit integer format)

Messages per Second	Baud Rate (bps) Required
1	600
2	1200
5	2400
12	4800
20	9600
30	14.4 K
60	38.4 K

Even at the slower communications rates, these data improve the capabilities of an existing Supervisory Control and Data Acquisition (SCADA) system. For a visualization-only system, an update rate of even once per second is suitable. Note that for use in an Energy Management System (EMS), even the slowest rates provide better data than traditional SCADA. State measurement can be performed with more accuracy and less system communication than state estimation. Communications processors are also used in substations to parse and separate the data and then send only necessary synchrophasor information, simplifying the initial use of this powerful new tool. If the communications latency and interpolling delay is significantly less than the desired application update requirements, all stations send data sampled at exactly the beginning of each second, fifth second, or tenth second. Communication of the complete IEEE PC37.118 protocol may present too much of a limitation for existing communications systems, such that a full implementation of a synchrophasor visualization or analysis system is not possible without a communications upgrade. However, existing communication will support collection and display of voltage angles, or other subsets of the complete synchrophasor message, within existing applications. Such synchrophasor data collection and display is at virtually no cost when the synchrophasor data come from devices, such as protective relays or meters, that already include this capability.

MID-RANGE COMMUNICATIONS REQUIREMENTS

To take advantage of the capability of synchrophasors to improve system operations, one needs more than just positive-sequence voltage magnitude and angle. As the power system sends additional voltage and current phasors, the communications requirement will also increase. For example, for data transmission using IEEE PC37.118 protocol, sending three-phase voltages and six-phase currents and system frequency will require communications rates listed in Table 2.

Table 2 Communications Rates for Three-Phase Voltage, Six-Phase Current, and Frequency Synchrophasor Information (16-Bit Integer Format)

Messages per Second	Baud Rate (bps) Required
1	1200
2	2400
5	9600
20	28.8 K
30	38.4 K

This information, especially at the faster data rates, supports sophisticated visualization and other more data-intensive analysis. Synchrophasors are being used for analysis of system events and determining system performance [6]. For these purposes, speeds of 20 and 30 messages per second are necessary; algorithms under development require 60 messages per second or even higher data rates. At these levels, broadband communication will certainly be necessary. Keep in mind that the communications rates shown in the tables are from a single phasor measurement unit with only two line currents and one bus voltage. It is certainly reasonable to have a station sending in data from six or eight lines and two or three buses. For more advanced systems, it is possible to send additional analog and digital information, as well as to use floating point information instead of fixed point information. For a single PMU, transmission of such information would lead to maximum data rates such as those listed in Table 3.

Table 3 Maximum Transmission Rates From a Single PMU (32-Bit Floating Point Format)

Messages per Second	Baud Rate (bps) Required
1	2400
2	4800
4	9600
10 / 12	28.8 K
20	57.6 K

This information includes three-phase voltage and positive-sequence voltage, six-phase currents and two positive-sequence currents, frequency and rate of change of frequency, and eight additional analog bits and 32 additional digital bits. The limit of 57.6 Kbps is from the serial port of the PMU in use.

Data Storage Requirements

For event analysis, it is necessary to record synchrophasor information for retrieval after an event. How long should such data be stored? This question cannot be answered easily. In the August 14, 2003 blackout referenced earlier, there was evidence of system oscillations days before the blackout. On a larger scale, it is reasonable for one to compare event data to data from a prior year to assess the impact of added generation or loads. For comparison of the three data requirements, refer to Table 4.

Table 4 Archiving Requirements for 8 PMUs for 30 Days

Messages per Second	Minimal Archiving	Medium Archiving	Maximum Archiving
1	570 Mb	2.09 Gb	5.14 Gb
2	1.11 Gb	4.17 Gb	10.29 Gb
4	2.22 Gb	8.34 Gb	20.58 Gb
5	2.78 Gb	10.43 Gb	25.72 Gb
10	5.56 Gb	20.86 Gb	51.45 Gb
12	6.67 Gb	25.03 Gb	61.74 Gb
20	11.12 Gb	41.71 Gb	102.89 Gb
30	16.69 Gb	62.57 Gb	
60	33.37 Gb		

Data comparison reduces storage size. A reasonable synchrophasor system would have 10 to 100 PMUs. Archiving annually would involve a significant commitment of storage assets and is not unlike requirements for digital fault recorders. Because there may be minimal changes from one sample to another, techniques within advanced database structures compress these data to reduce the required storage space. Instead of being stored in central storage, data are stored on-site until an event calls for data retrieval. The data are then physically transported to a central location for analysis.

Conclusion

Communication and synchrophasor applications go hand in hand. Neither stands alone, and both must recognize the requirements and limitations of the other.

1. Communication is key to synchrophasor technology achieving optimal asset utilization.
2. Care is necessary in determining measurement requirements.
3. A staged implementation of synchrophasor technology will allow communication to expand with the natural expansion of data use.
4. Data must be communicated to the application or user in a way suitable for the intended use.

ACKNOWLEDGMENT

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BIOGRAPHY

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. He is now a senior product manager. Prior to joining SEL 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 the State of Pennsylvania.

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