All the Data Fit to Print – Applying All the Available Synchrophasor Information

Bill Flerchinger, Roy Moxley, and Eren Ersonmez
Schweitzer Engineering Laboratories, Inc.

Presented at the
11th Annual Clemson University Power Systems Conference
Clemson, South Carolina
March 13–16, 2012

Previously published in the
proceedings of the 2nd Annual Protection, Automation and Control World Conference,
June 2011

Originally presented at the
13th Annual Western Power Delivery Automation Conference, March 2011

All the Data Fit to Print – Applying All the Available Synchrophasor Information

Bill Flerchinger, Roy Moxley, and Eren Ersonmez, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—Synchrophasor measurements have become a byword in the smart grid lexicon. What is not so well known is that an IEEE C37.118 synchrophasor message includes much more than the phase angle and magnitude of selected electrical quantities. This paper discusses all of the elements of the synchrophasor message. The derivations of these elements, as well as the way they are and can be applied, are considered.**

This paper discusses the time value of different available measurement types (i.e., how critical the time measurement is to these different measurements and how that impacts connected automation schemes).

Message size is also discussed as a function of information selected in the data stream and its impact on communication and data storage.

By combining knowledge of all the information that is available in synchrophasor-based systems with transmission, storage, and data usage examples, this paper provides a tutorial for synchrophasor applications both today and into the future.

I. Introduction

The IEEE C37.118-2005 standard defines synchronized phasor measurements as well as the message format for communicating these data in a real-time system. While most think of this standard with regards to sending time-coherent voltage and current phasors, IEEE C37.118 messages can be used to provide much more information. This paper discusses all of the elements included in IEEE C37.118 messaging and how to use this efficient messaging to provide real-time information from across the system. Technically, IEEE C37.118 messaging can be used to replace other systems for communicating information about the system.

As the name implies, synchrophasors are a synchronized measurement of power system quantities in phasor format. The first great advance in the application of this technology was to establish a reference point [1] for these measurements, as shown by the reference wave of Fig. 1 [2]. This reference is defined as a cosine wave with its peak at the beginning of each second and continuing at exactly the nominal frequency. Local measurements are then compared to this reference, as shown in Fig. 1b.

Traditional information management systems and protocols that are used to communicate information back to a central location (e.g., DNP3, Modbus®, or OPC) send magnitude measurements only. These systems update information every few seconds to every few minutes. Additionally, the data are not time-coherent or time-stamped, making it difficult to accurately assess system conditions. Using synchronized measurements overcomes these shortcomings and provides many additional benefits.

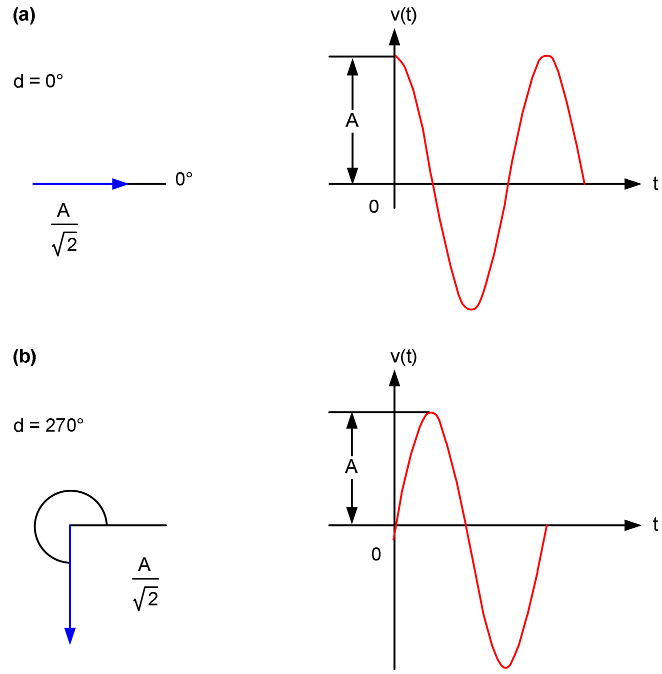


Fig. 1. Reference wave (a) and local wave (b) with angular comparison

II. Type and Structure of IEEE C37.118 Messages

Experience with using IEEE 1344 showed shortcomings in dynamic performance and operating requirements, so the standard was updated to IEEE C37.118. Today, this is the dominant protocol for communicating synchrophasor data. This standard includes requirements for synchrophasor measurements as well as a data communications protocol for exchanging synchrophasor data in real time. Less common protocols include PDCStream, Fast Message, and IEC 61850. The IEEE C37.118 protocol is a streaming protocol that can be sent at variable message rates from 1 to 60 messages per second, with even faster rates being considered.

This paper focuses on the commonly used IEEE C37.118 messaging and information available beyond phasors.

IEEE C37.118 defines a binary messaging format [3], but it does not require any specific medium or transport mechanism for communicating these frames. Most implementations today use Transmission Control Protocol/Internet Protocol (TCP/IP), User Datagram Protocol/Internet Protocol (UDP/IP), or EIA-232 serial communications. EIA-232 is commonly used within the substation or for transporting a small set of data from a single phasor measurement unit (PMU). In a wide-area system where there are multiple PMUs involved, IP networks are generally employed. Substations may be linked to each other and control centers by leased lines, privately owned synchronous optical networks (SONETs), wireless links, and so on.

There are four types of IEEE C37.118 message frames:

- Data
- Configuration
- Command
- Header

Clients send command frames to PMUs to either request configuration and header frames or to start or stop the data stream. Data frames include the actual data being sent in a raw binary form in an integer, floating-point, or Boolean format.

Configuration frames define the data frames so that clients can know how to interpret the raw bytes. Header frames are not commonly used today, but they are intended to transmit any general information about the PMU or the phasor data concentrator (PDC) in a text form.

IEEE C37.118 frames include common header fields (not to be confused with the header frame) in the beginning and a cyclic redundancy check checksum at the end.

A typical IEEE C37.118 conversation is shown in Fig. 2. The client requests a configuration frame from the PMU. After receiving the configuration frame, the client asks for the data stream. The PMU continues to send data frames until the client requests that it stop the data stream.

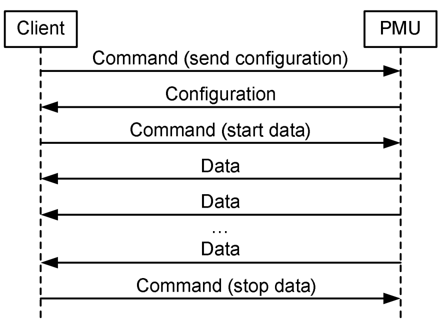


Fig. 2. Example IEEE C37.118 conversation

An IEEE C37.118 message uses the structure shown in Table I regardless of message type (each message includes these header fields).

TABLE I
IEEE C37.118 MESSAGE HEADER FIELD SUMMARY

Header Field	Description	Bytes
SYNC	Provides synchronization and frame type indication; Bits 4–6 designate the frame type (e.g., data, configuration, header, command)	2
FRAMESIZE	Communicates the total number of bytes in the frame, including the CHK bits	2
IDCODE	Identifies the individual PMU that is sending (or receiving) the message	2
SOC	SOC (second of century) and FRACSEC together provide the time stamp based on the count starting at midnight Jan. 1, 1970	4
FRACSEC	Includes a 24-bit actual fraction of a second integer and an 8-bit time-quality flag	4

Data frames include a status field, as well as measured values such as phasors, analogs and digitals, frequency, and rate of change of frequency (df/dt).

The information in the IEEE C37.118 message that we are interested in for the purposes of this paper is primarily located in the SOC, FRACSEC, ID code, and data frame-specific fields.

III. USEFUL INFORMATION SENT IN EVERY IEEE C37.118 DATA FRAME

Now that we know the type and structure of IEEE C37.118 messages, we will look at some of the useful information that is sent as part of the data message.

First, each data message includes a time stamp (or timing information) that is accurate to better than 1 microsecond. This is located in the SOC and FRACSEC header fields and provides time-coherent data from across the entire system. Remember that all PMUs are connected to Global Positioning System (GPS) satellite-synchronized clocks; thus it is very easy to look at time-aligned data from across the entire network. The time-coherent data from the PMUs make it possible to see the exact time sequence of the data. Each data message has the unique PMU ID code for these data. This indicates the exact PMU that each data stream came from.

Also included in the FRACSEC field are 4 bits that indicate the status of the GPS clock. These bits convey that the GPS clock is locked and operating as expected, the clock is unlocked and operating with reported time accuracy, or there is an error and the clock time is not reliable. This provides confidence that each data message is accurately time-stamped.

A. PMU Status Information

A significant amount of useful information is sent as part of the 2-byte, or 16-bit, status word within a data field. The bits that may be most useful are listed in Table II.

TABLE II
DATA FIELD STAT BIT SUMMARY

Bit(s)	Description	Status
0–3	Identifies the specific PMU trigger that has been sent	Triggers include manual, magnitude high, frequency high/low, phase angle difference, df/dt high, digital, or user-defined triggers
4, 5	Communicates if the PMU is synchronized and locked to the clock and, if not, how long it has been unlocked	Status includes: locked, unlocked for 10 seconds, unlocked for 100 seconds, unlocked for 1000 seconds
10	Indicates that the PMU configuration has been changed	Sets a flag for 1 minute when the configuration has been changed
11	PMU trigger detected	Single bit indicates if any of the PMU triggers have occurred
13	PMU synchronization	Indicates PMU is synchronized with clock
14	PMU error	Indicates there is a PMU error
15	Data valid bit	Indicates if the PMU is in test mode or not

B. Uses of Status Bits

We can use Status Bits 13, 14, and 15 to ensure that data being sent for the PMU are, in fact, valid and time-synchronized data. Additionally, Bit 10 can be used as an alert when there has been a PMU configuration change. This can be important to maintain accurate PMU configuration information. Bits 4 and 5 provide insightful information about the clock synchronization to the PMU. By monitoring and recording these bits, it is possible to detect intermittent clock outages. Furthermore, these bits can be used to quantify the length of the outage. This can be useful in cases where there is either a faulty clock or the antenna to the clock is partially blocked, limiting reception of the GPS signal.

Bits 0 through 3 are useful for capturing various trigger conditions in the PMU. In addition to the predefined trigger conditions, the user can define unique triggers. As mentioned previously, IEEE C37.118 messages are always streaming. This means that it is possible to know immediately when any of the above bits are toggled, thus providing real-time status or triggering an alarm back at a central location or engineering office.

C. Information in the Data Fields

Information in the data fields includes the following:

- Phasors (voltage and current, both magnitude and angle)
- Frequency and df/dt
- Analog values (any analog measured value or calculated values using measured quantities)
- Digital values (any digital status state, such as a 1 or 0 state)

Each time-stamped message sent by a PMU includes all of this information in the data fields of the message. Obviously, the IEEE C37.118 standard was developed specifically for defining and communicating synchronized phasor measurements. Real-time, time-coherent measurements of voltage (magnitude and angle), current (magnitude and angle), frequency, and df/dt from across a wide area lend themselves to many applications.

Status bits become a critical part of real-time control systems using synchrophasors, but judgment must be applied in recognizing their importance for a particular control scheme, as in the following examples.

1) Example 1

Phase angle across a power system has been used to directly control generator shedding on excess power transfer [4]. In this case, the data should be qualified with a status bit to ensure that timing is accurate. If timing were lost at either end of the system, then the phase angle would not be accurate, leading to a loss of scheme reliability.

2) Example 2

Because synchrophasor data are streamed, they can be a useful source of operating quantities, even if exact timing is not important. In one case of a static VAR control (SVC), voltage magnitude from a remote location is brought into the control scheme to prevent overvoltage [5]. In this case, if the time signal were lost, the voltage magnitude would still be accurate and valid for control purposes.

The point of these examples is that there is no overriding rule for using the status bits. Phase angle data require accurate time at all locations. Magnitude or other analog data may not require an accurate time stamp.

IV. USING ADDITIONAL IEEE C37.118 DATA IN PROVEN CONTROL SCHEMES

As mentioned, the synchrophasor data field includes analog and digital values. These are frequency, df/dt, voltage and current phasors, and any digital or analog available to the PMU. Applications that use synchrophasor-based phasor and frequency measurements have synchronized portions of the network or generation to a network [6] and detected an islanded condition for distributed generation [7]. In each of these examples, data beyond the phasors were involved in the direct application to improve the function of the schemes.

A. *Synchronizing Generation to a Network*

Using PMUs, located on either side of a synchronizing circuit breaker, that stream angle, magnitude, frequency, and df/dt to a PDC and a visualization system, it is possible to either manually close the breaker or to adjust the governor on islanded generation (Fig. 3) [6].

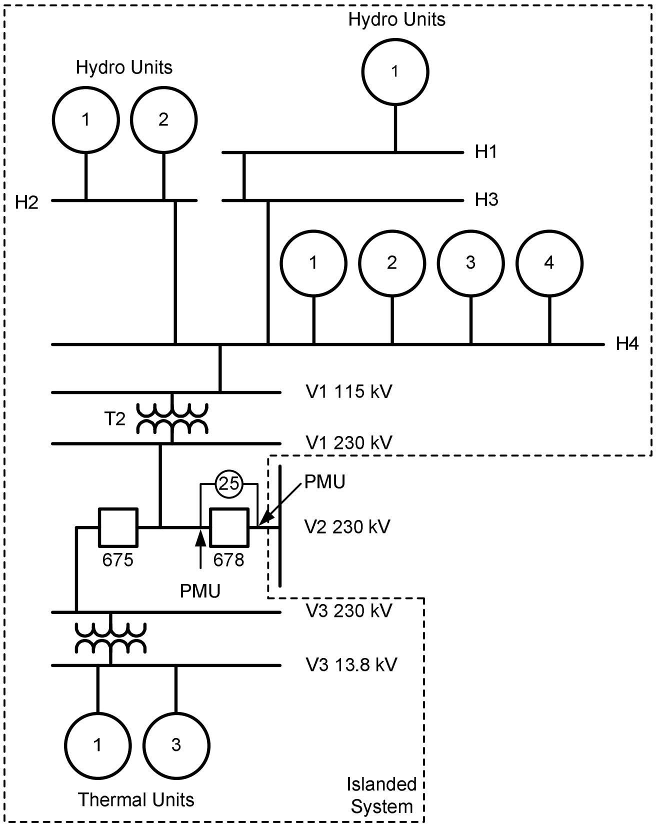


Fig. 3. Synchronizing an islanded system

In this case, only phasors and slip frequency need to be compared to properly synchronize the system, but adding digital information will enhance the security of the scheme. Consider the manual synchroscope shown in Fig. 4.

Fig. 4. Manual synchroscope with voltage, frequency, and two indicator lights

An operator using this traditional method to synchronize the system will observe the phase angle difference on the synchroscope but also see the voltage and frequency of both buses. The indicator lights just below the synchroscope will go from light to dark as the systems go in and out of phase. IEEE C37.118 data can be provided to fill this function as well. Voltage magnitude differences alert an operator or automated system to potential excessive power flows following synchronization. Comparing the frequency information from each PMU conveys how fast frequency is changing between the two PMUs (i.e., the slip frequency between the two PMUs), similar to how an operator observes the indicator lights changing their rate of blinking. Additionally, data bits on PMU status and time synchronization validate the data quality for automated schemes.

B. *Detecting an Islanded Condition for Distributed Generation*

Reliably detecting an islanded condition with distributed generation (DG), even when the load and generation are closely matched in less than 2 seconds as required by IEEE 1547, can be challenging (Fig. 5).

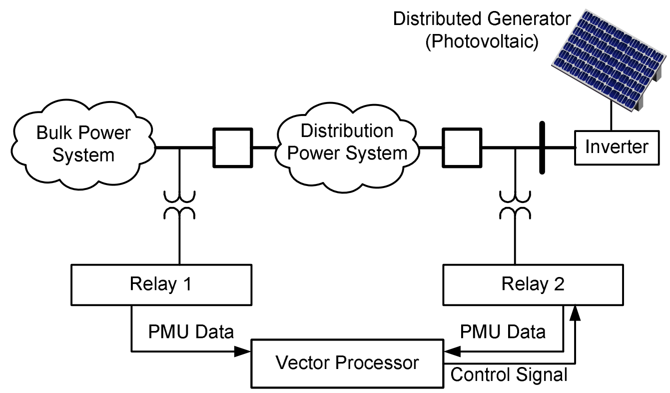


Fig. 5. Anti-islanding scheme using an inverter and synchrophasors

Placing a PMU at the DG site and another at the substation provides for streaming angle data at 60 messages per second from both PMUs to a vector processor located at the DG site to calculate slip and acceleration based on voltage angles. If predetermined levels of angle, slip, and/or acceleration are exceeded, as shown in Fig. 6, then a control signal is sent to trip off the DG [7].

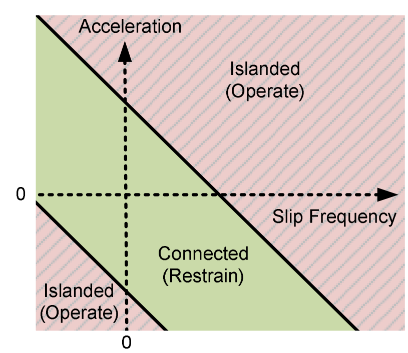


Fig. 6. Islanding detection characteristic using slip and acceleration [7]

By using voltage angle measurements and local detection techniques, it is possible to reliably detect and trip the DG in less than 2 seconds, but it should be noted that this is an automated scheme using remote data. In addition to data quality information, such as suggested in previous examples, it would be advantageous to use the PMU ID sent with the message header to ensure that the correct PMUs are applied for comparison. Using the configuration change data bit ensures that no change in the remote settings has been made.

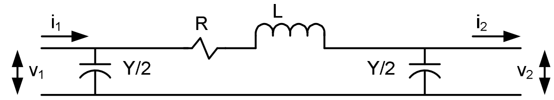
These and many other applications make use of the magnitude, angle, and frequency measurements that the IEEE C37.118 standard was developed for. While we have summarized just two examples of how IEEE C37.118 phasor and frequency data can be used, there are many different applications that these data can be used for.

C. Using Analog Data for Future Applications

Analog data can be used for sending measured and calculated values, specifically by using phasor measurements and performing calculations in the PMU and then sending the calculated values as analog data represented by either a 16-bit integer or a 32-bit floating-point value. Calculations can also be performed on any analog data measured. Examples of calculated values that could be of interest include the apparent impedance of a line or load using the voltage and current magnitude and angle measurements, the power flow and direction of power flow on a line, and the temperature of a line based only on voltage and current measurements.

External measurements can be brought into the PMU as analog values using transducers and analog Generic Object-Oriented Substation Event (GOOSE) messages in IEC 61850 protocol. Using analog inputs on the PMU allows measurement of quantities such as bearing pressure, oil levels, temperatures, shaft speed, and transformer tap positions. As an example, a resistance temperature detector (RTD) that measures temperatures in the range of –50° to +250°C is connected to a device that is connected to the serial input of a PMU. The RTD can be used to accurately measure the temperature of transformers, breakers, motors, or generators at multiple points, providing additional insight into the operation of the equipment. Analog values can also be brought into the PMU using a programmable automation controller. A typical programmable automation controller will be connected to analog inputs and send these inputs via an IEC 61850 GOOSE message to a PMU for inclusion in the analog data sent. As mentioned, any analog value can be measured using the appropriate transducer to bring the measured quantities into the PMU. Time-stamped data provide valuable information about the operation of equipment located in the substation. One example of how analog values can be used is to measure temperature to determine dynamic load limits.

The use of synchrophasors to dynamically measure system parameters, such as line impedance, has been tested with the goal of improving accuracy [8]. Line loading based on real-time temperature measurements or calculations provides significant economic benefits. The complicating factor of using synchrophasors for measuring temperature from line resistance comes from the accuracy needed in angular measurement. Consider the equations derived from a pi system model, as shown in Fig. 7.



$$Y = \left[(i_1 - i_2)/(v_1 + v_2)\right] \bullet 2$$
$$C = \text{Im}(Y)/2\pi f$$
$$Z = \left(v_1^2 - v_2^2\right)/\left(i_1 v_2 + i_2 v_1\right)$$
$$R = \text{Re}(Z)$$
$$L = \text{Im}(Z)/2\pi f$$

Fig. 7. Pi system model solving for line parameters

Because all of the voltage and current values in the equations shown in Fig. 7 are phasor quantities, a small error in angle will result in a large error in resistance. Long lines (typically over 100 kilometers) and heavy loading minimize this error. The error can also be minimized by having a reference temperature to compare with the synchrophasor calculated value. A PMU with access to an ambient temperature input can use that information, along with time, date, and geographical information, to calculate line temperature [9]. Transmitting this calculated value as an analog quantity, along with phasor data to be used in calculating temperature, provides both a reality check and a reference value that can be used as a calibration point.

D. Using Digital Data to Communicate Synchronized Status Information

The IEEE C37.118 message contains 2 bytes, or 16 bits, of digital status words. These digitals are perfect for efficiently communicating the status of equipment on a real-time basis because a single bit can communicate a 1 or 0 status of a device. Because synchrophasor data are constantly streaming, they also provide this status simultaneously with other information, like the current and voltage phasors and analog data, as the event occurs. Digitals are often used to communicate breaker status, recloser count or position, or disconnect switch status. Another way that digitals can be utilized is to connect alarm contact outputs to the digital inputs. This provides a time-stamped record of all alarms that occur. These could be the alarm contacts of the relay itself or any other piece of equipment in the substation. Furthermore, the digital inputs can be used when a predetermined set point or limit is exceeded. Examples of this include various generator set points, overtemperature conditions, exceeded bearing pressure limits, and vibration alarm trips. When the predetermined condition is exceeded, the digital value in the IEEE C37.118 message reflects this in the next message sent, thus providing an operator or other personnel instant notification that a problem or condition exists.

One last point to mention regarding the use of digital data bits in the IEEE C37.118 message stream is that in cases where there is a limited amount of communications bandwidth out of a substation, digital data bits are an effective way to communicate information. By only using 16 bits of an IEEE C37.118 message, streaming information can be sent that indicates when alarms and predetermined set points are exceeded for up to 16 different inputs. This allows this information to easily be sent using a low data rate communications channel like a 19.2 kilobits per second frame relay line. Thus, even in cases where there is limited communications bandwidth, IEEE C37.118 messaging can provide valuable, real-time information about the equipment or operating status of the substation.

V. Data Management

A. Message Size and Storage Requirements

The IEEE C37.118 messaging protocol was designed to be very efficient, in terms of communications bandwidth, to send information. Because this is a streaming protocol, data are constantly being sent at selectable message rates between 1 and 60 messages per second. The combination of user-selectable data (phasors, analogs, and digitals) and the message rate allows the user to adjust the needed communications bandwidth with what is available to a given site. Furthermore, being creative with how to send information using the digital words in the IEEE C37.118 message can further minimize the communications bandwidth needed. Alternatively, if there is plenty of communications bandwidth out of the substation, then maximizing the information sent in the IEEE C37.118 message at 60 messages per second can provide a more complete picture of the operating conditions and status of the system and components in the system. Fig. 8 and Fig. 9 provide a few example bandwidth requirements to help understand the needed bandwidth using either serial or Ethernet communications.

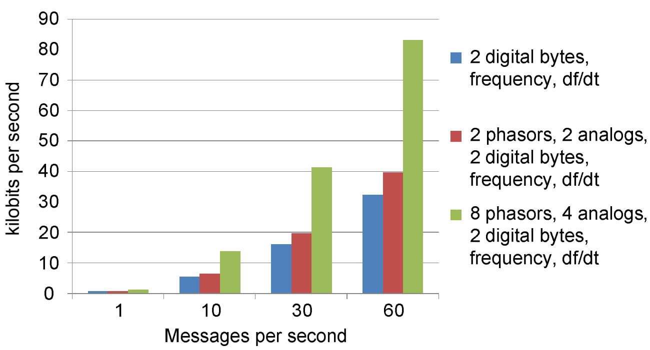


Fig. 8. Serial communications bandwidth

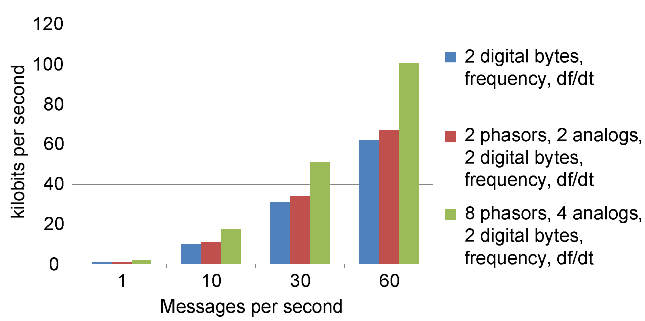


Fig. 9. Ethernet communications bandwidth

As can be seen, streaming IEEE C37.118 messages can be sent over limited communications bandwidth if that is all that is available or can use a fair amount of bandwidth if needed to send more information at a very high message rate.

B. Archiving IEEE C37.118 Data

Not all applications require using IEEE C37.118 real-time messages. Archiving synchrophasor data is valuable for post-event or offline analysis. This allows the user to look at time-coherent data from across the system and correlate measured data and events. Additionally, offline analysis can be used to validate or improve system models and to identify operational or device-specific trends. Furthermore, continuously archiving data at a minimum of 6 messages per second can be used as part of a solution to meet the North American Electric Reliability Corporation (NERC) PRC-002-2 disturbance recording requirements for dynamic disturbance recording. Last, pulling sequence of event data and fault recording data from certain relays and storing this information allow complete compliance with the PRC-002-2 disturbance recording requirements. Fig. 10 and Fig. 11 provide an indication of the needed storage requirements for archiving IEEE C37.118 data.

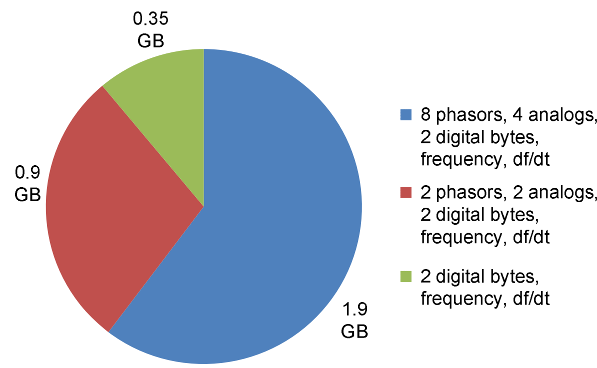


Fig. 10. Monthly archive storage requirements (with data archived at 10 messages per second)

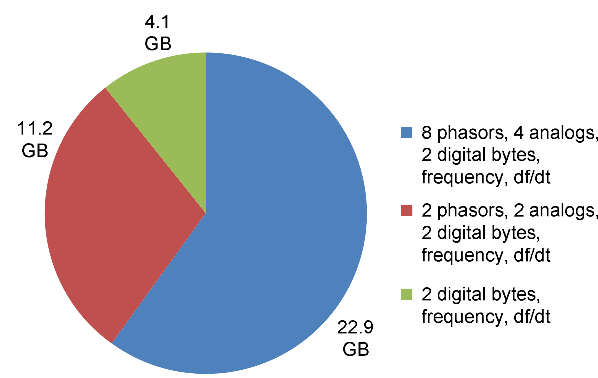


Fig. 11. Yearly archive storage requirements (with data archived at 10 messages per second)

C. Securing IEEE C37.118 Data

Since we are communicating important information into and out of the substation, we need to consider steps to ensure that these data are properly secured and follow good cybersecurity practices.

IEEE C37.118 defines a binary messaging format, but it does not require any specific medium or transport mechanism for communicating these frames. Implementations today use TCP/IP, UDP/IP, and EIA-232. EIA-232 is typically only used locally between a single PMU and the PDC, transporting a smaller set of data. Occasionally, EIA-232 is used to communicate the IEEE C37.118 messaging out of the substation. Wide-area communications typically use IP networks to transport synchrophasor data because of the increased data bandwidth required from multiple PMUs or PDCs.

Designing in Critical Infrastructure Protection (CIP) compliance is good business practice, and we recommend applying as many of the NERC CIP requirements as are technically and economically feasible when designing and implementing the system. Two aspects to consider when developing a plan to implement cybersecurity for the synchrophasor system are substation security and information security.

To protect substations from external cyberattacks, a best practice is to build an electronic security perimeter around the substation network and closely control all access points into and out of this network. The key is to minimize the number of electronic access points, thus minimizing the points of exposure to external threats.

Another best practice is to use a multilayered architecture. In a multilayered architecture, all devices that are connected directly to the power system are separated from external access points by first passing through protective layers (Fig. 12). Protective layers include sending PMU data to a PDC and then sending the output of the PDC through a secure Ethernet gateway.

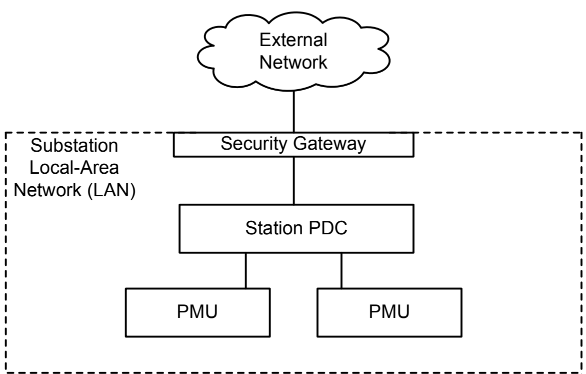


Fig. 12. Multilayer system architecture

This architecture reduces the likelihood for a hacker to gain access to, much less take control or change the settings of, the relays and/or PMUs. Additionally, in this system architecture, all communications must first go through a secure Ethernet gateway. The gateway acts as a firewall (which should be configured to block all traffic unless explicitly allowed by a rule—a deny-by-default approach) and as a virtual private network (VPN) to encrypt and secure the data into and out of the substation. Gateways are used on each end of each of the communications links to secure the information sent on the link between them. All devices in a multilayered architecture should have all unused ports and services disabled to further minimize the chance of unauthorized access. If serial communications are used for sending data outside the substation, a serial encryption device should be used on each of the communications links.

Another way to secure access to the substation communications path from which the data are being sent is to configure the PMU and/or PDC output to use unidirectional synchrophasor data streams. By using UDP Secure (UDP_S), the PMU or PDC sending the data neither expects nor accepts any incoming message streams, thus eliminating the possibility that a hacker could access the PMU or PDC.

A cyberattack can target the synchrophasor data coming out of the substation rather than the substation itself. Therefore, it is important to securely transport the data from the substation to the end applications.

Substations are connected to other substations and control centers through a variety of communications links. These links may or may not be in the control of the utility. We recommend treating all links as untrusted links. To protect data confidentiality and integrity, it is best to encrypt data going across these links. Data encryption can be done at the link layer (using serial encryption or SONET encryption devices) or at the IP layer (using a VPN to encrypt and secure the synchrophasor data from the rest of the network routable traffic).

VI. Conclusions

Although the IEEE C37.118 standard was developed for defining synchronized phasor measurements as well as the message format for communicating these data in a real-time system, the messaging protocol can be used beyond its original intention. Additionally, because the protocol is very efficient at sending data and does not require any specific medium or transport mechanism for communicating the data, it can be used in a variety of applications.

Information that is sent in an IEEE C37.118 message includes voltage and current phasors, frequency, df/dt, any analog measured value, and any digital status that can be input into the relay and/or PMU. All of the data are sent with microsecond-accurate timing information and unique PMU identification as well as a wealth of status bits that help to ensure that the data received are valid and good. Because IEEE C37.118 is a streaming protocol, information is delivered on a near real-time basis. Furthermore, the message rate of this streaming protocol is user configurable, allowing the data bandwidth of the streaming protocol to be matched with the bandwidth available at various substations or throughout the network.

The IEEE C37.118 protocol can be used to replace existing data collection systems and protocols. One benefit of using the IEEE C37.118 protocol is that all measured data are time-stamped, allowing easy correlation of events across the system. Another benefit is that because it is a streaming protocol, the user knows immediately if the data are valid, because no measurements are available if the communications channel goes down or the measuring relay and/or PMU is not functioning.

Use all of the available information in the IEEE C37.118 message to get the maximum benefit out of these streaming data.

VII. References

[1] IEEE Standard for Synchrophasors for Power Systems, IEEE 1344, 1995.

[2] R. Moxley, "Synchrophasors in the Real World," proceedings of the 7th Annual Western Power Delivery Automation Conference, Spokane, WA, May 2005.

[3] IEEE Standard for Synchrophasors for Power Systems, IEEE C37.118-2005, 2005.

[4] A. Jarquin, E. M. Alcaraz, E. G. Alcantar, and J. L. Eternod, "Reliability Analysis for a Generation Shedding Scheme on the CFE Main Transmission Network," proceedings of the 29th Annual Western Protective Relay Conference, Spokane, WA, October 2002.

[5] A. Johnson, R. Tucker, T. Tran, J. Paserba, D. Sullivan, C. Anderson, and D. Whitehead, "Static Var Compensation Controlled via Synchrophasors," proceedings of the 34th Annual Western Protective Relay Conference, Spokane, WA, October 2007.

[6] K. Koellner, C. Anderson, and R. Moxley, "Generator Black Start Validation Using Synchronized Phasor Measurement," proceedings of the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

[7] M. Mills-Price, M. Scharf, S. Hummel, M. Ropp, D. Joshi, G. Zweigle, K. G. Ravikumar, and B. Flerchinger, "Solar Generation Control With Time-Synchronized Phasors," proceedings of the 37th Annual Western Protective Relay Conference, Spokane, WA, October 2010.

[8] D. Shi, D. J. Tylavsky, N. Logic, and K. M. Koellner, "Identification of Short Transmission-Line Parameters From Synchrophasor Measurements," proceedings of the 40th North American Power Symposium, Calgary, Canada, September 2008.

[9] G. Benmouyal, M. B. Bryson, and C. Anderson, "Implementation of the SEL-49 Relay Line Thermal Protection in the SEL-421 Relays Using SELOGIC Equations," SEL Application Guide (AG2003-06), 2004. Available: http://www.selinc.com.

VIII. Biographies

Bill Flerchinger is a lead marketing engineer for synchrophasor-based solutions at Schweitzer Engineering Laboratories, Inc. (SEL). Prior to joining SEL, he worked for Agilent Technologies, Mobile Broadband Division, as the product planning manager. He recently completed a Certificate in Transmission and Distribution from Gonzaga University. Bill received his M.S. in Engineering Management and a B.S. in Electrical Engineering from Washington State University.

Roy Moxley has a B.S. in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories, Inc. (SEL) 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.

Eren Ersonmez is an integration and automation engineer at Schweitzer Engineering Laboratories, Inc. He focuses on communications and security of distributed synchrophasor systems. Eren participates in the NASPInet development efforts within the NASPI Data and Network Management Task Team. He previously worked as a software engineer for a major semiconductor manufacturer. He received his B.S. in Information Systems from the University of Idaho.