



Applying All the Available Synchrophasor Information

Roy MOXLEY, Greg RZEPKA, Eren ERSONMEZ, Bill FLERCHINGER
Schweitzer Engineering Laboratories, Inc.
USA
Roy_Moxley@selinc.com

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1 INTRODUCTION

The enabling technology behind synchrophasors is the capability to receive an exact time signal anywhere on the electric power system. The first IEEE standard provided for a way to use this time signal to compare electrical quantities received from anywhere on an electric grid [1]. The succeeding standard, IEEE C37.118, provided for off-nominal frequency performance and added extra data as part of the synchrophasor message [2]. The standard for these phasor measurements is shown by the reference wave of **Fig. 1** [3]. 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**.

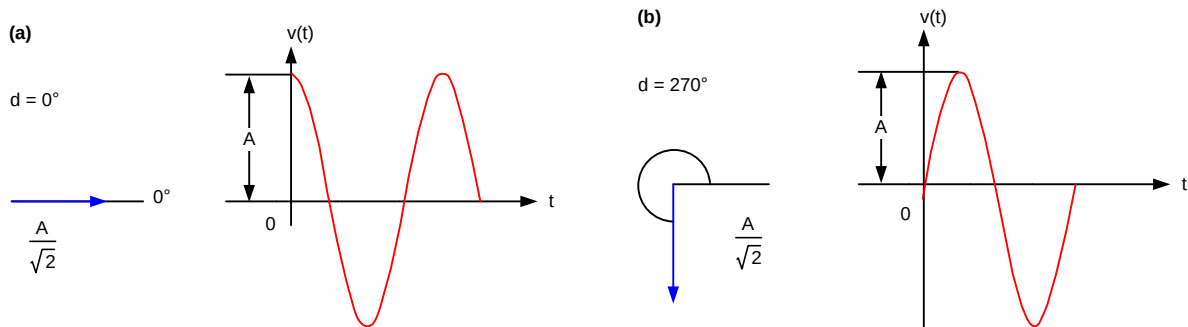


Fig. 1: Reference wave (a) and local wave (b) with angular comparison

Traditional information management systems (e.g., DNP3, Modbus[®], or OPC) send magnitude and status measurements only. These systems update information every few seconds or minutes. The data are not synchronized, making it difficult to determine system conditions. Using synchronized measurements of electrical quantities and status values provides many additional benefits.

2 BACKGROUND

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 measurements as well as a data communications protocol. 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 information available beyond phasors. Traditional electric utility protocols include binary information, such as breaker and disconnect switch status, along with analog data, such as current magnitude. Synchrophasor messaging adds to the usefulness of these data.

IEEE C37.118 defines a binary messaging format [2], 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 various communications networks.

Overall signal latency can become a factor if the synchrophasor measurements are used for real-time control systems, such as generator control [4] or control of active devices [5] in the power system. In the case of using synchrophasor data to close circuit breakers [6], the latency of the signal directly determines the maximum slip frequency that can be allowed prior to closing the breaker. Typical times range from just a few milliseconds to 1 second. As signals are concentrated, the latency of the phasor data concentrator (PDC) must also be considered. Hardware PDCs for substation application are available with latencies of as little as 10 milliseconds, while some software systems running on commercial operating systems have latencies of up to one-half second or more.

There are four types of IEEE C37.118 message frames: data, configuration, command, and header. Each of these categories has aspects that make it reasonable to use in different synchrophasor systems. Clients send command frames to PMUs to either request configuration and header frames or 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 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.

3 IEEE C37.118 MESSAGE STRUCTURE

An IEEE C37.118 message uses the structure shown in Table 1, regardless of message type. Each message includes these header fields.

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 unit 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

Table 1: IEEE C37.118 Message Header Field Summary

Note that each message has the ID CODE of the sending PMU. Considering that the data are frequently sent over switched networks (serial or Ethernet), this is an important consideration to control systems. 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).

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.

4 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.

Included in the FRACSEC word are 4 bits that indicate the status of the Global Positioning System (GPS) clock. These bits convey that the GPS clock is locked and operating as expected, the clock is unlocked and operating with a reported time accuracy, or there is an error and the clock time is not reliable. This provides confidence to the user that each data message is accurately time-stamped and also provides a data bit that can be used in control equations to block bad data.

4.1 PMU Status Information

Much 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 2.

Bit(s)	Description	Status
0–3	Identifies the specific PMU trigger that has been sent	Triggers can be selected as any quantity available to the PMU, including electrical quantities (v, i, f, df/dt, or other) or status values, such as breaker status
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 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

Table 2: Data Field STAT Bit Summary

4.2 Uses of Status Bits

From the various Status Bits, we can use Bits 13, 14, and 15 to ensure that data being sent for the PMU are, in fact, valid and time-synchronized data. Bit 10 can be used to alert a user when there has been a PMU configuration change, which could cause an error in control logic using the PMU data. By monitoring and recording Bits 4 and 5, it is possible to detect intermittent clock outages and correlate them to other events. Furthermore, these bits can be used to quantify the length of the outage as well as identify a faulty clock or that the antenna to the clock is partially blocked, limiting reception of the GPS signal.

Trigger Bits 0 through 3 are useful for capturing various trigger conditions in the PMU that can be used for direct information or to initiate recording of data for a specified period.

4.3 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 the above 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.

4.3.1 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. Underfrequency data, either in the form of a digital bit or an analog value, could also be used to prevent generator tripping during events when generators need to stay online.

4.3.2 Example 2

Because synchrophasor data are streamed, they can be a useful source of operating quantities, even if exact timing is not important. In a static VAR control (SVC), voltage magnitude from a remote location is brought into the control scheme to prevent overvoltage [5]. 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.

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

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.

5.1 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. 2**).

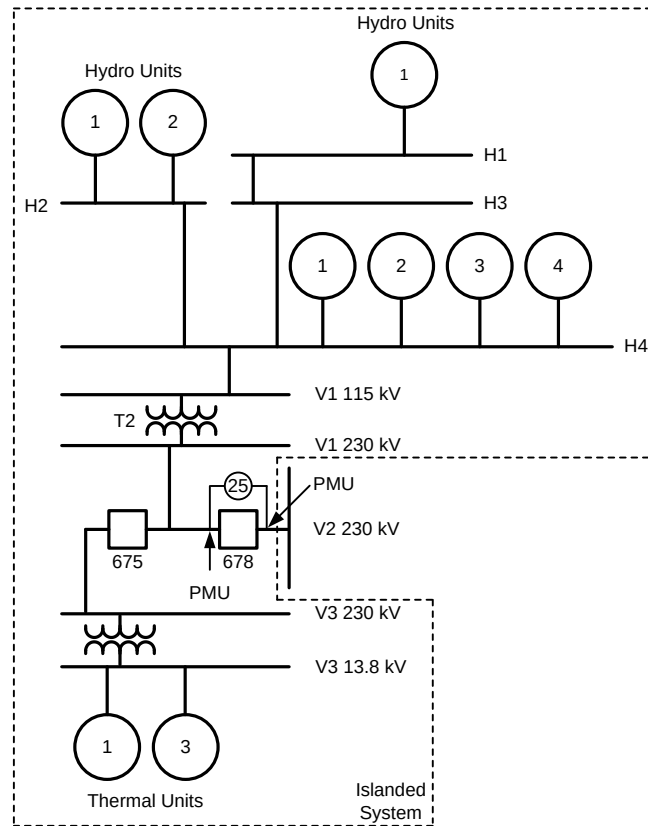


Fig. 2: Synchronizing an islanded system

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. 3**.

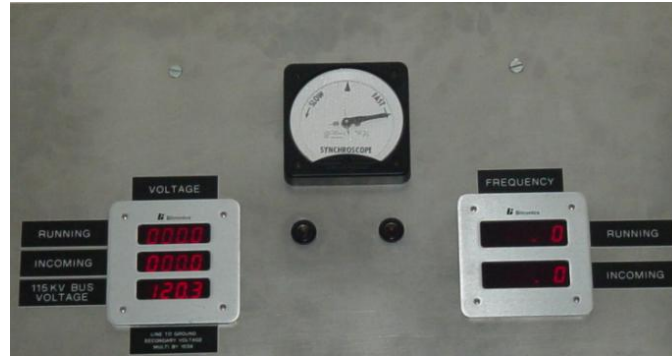


Fig. 3: Manual synchroscope with voltage, frequency, and two indicator lights

An operator using this traditional system to synchronize the system will observe the phase angle difference as well as the voltage, frequency, and a visual indication of the voltage difference and slip frequency from the indicator lights. IEEE C37.118 data can be provided to incorporate these functions as well. Additionally, data bits on PMU status and time synchronization validate the data quality for automated schemes.

5.2 Using Non-Phasor Analog Data

Analog data can be used for sending measured and calculated values, specifically by using phasor measurements (as well as other local inputs) 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 calculating the apparent impedance of a line or load using the voltage and current magnitude and angle measurements and calculating power flows and direction of power flows on lines. It may be possible to calculate the temperature of a line based on voltage and current measurements using an ambient temperature input to normalize the data.

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 the 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 $+250^{\circ}\text{C}$ 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 equipment. Analog values can also be brought into the PMU using a programmable automation controller (PAC). A typical PAC 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. PMUs can send multiple analog quantities in a single synchrophasor message. All of the quantities are referenced to the message time tag.

5.3 Measuring Temperature to Determine Dynamic Load Limits

Using synchrophasors to dynamically measure system parameters, such as line impedance, has been tested with the goal of improving accuracy [8]. Accurate dynamic line rating provides for improved line use, especially under system stress conditions. 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. 4**.

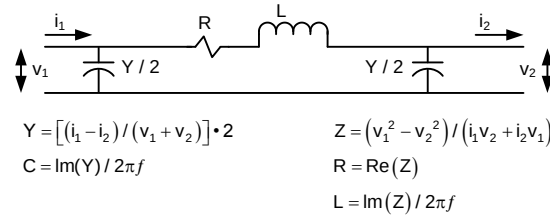


Fig. 4: Pi system model solving for line parameters

Because all of the voltage and current values in the equations shown in **Fig. 4** 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 bringing temperature data into the PMU and performing analog calculations of 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.

5.4 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 synchrophasor data are constantly streaming, they provide status information as events occur simultaneously with other information, like the current and voltage phasors and analog data.

In stations with a limited amount of communications bandwidth, the 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 values. 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.

5.5 IEEE C37.118 Message Size and Storage Requirements

The IEEE C37.118 messaging protocol was designed to be an efficient system to send information. Because this is a streaming protocol, data are constantly being sent at user-selectable message rates between 1 and more than 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. 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. Rates can vary from 9600 bps to 115000 bps or higher.

5.6 Archiving IEEE C37.118 Data

Not all applications require using the 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. Additionally, offline analysis can be used to validate or improve system models and to identify operational or device-specific trends. Furthermore, continuously archiving data provides dynamic disturbance recording. Last, pulling sequence of event data and fault recording data from relays and storing this information allow a user to completely meet disturbance recording requirements. Storage requirements range from 3.2 GB per month to store 2 phasors, 2 analogs, and 2 digitals, to 27.6 GB per year to store 8 phasors, 4 analogs, and 2 digitals.

5.7 Securing IEEE C37.118 Data

Critical data require that we 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. Two aspects to consider when developing a plan to implement cybersecurity 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. Protective layers include sending PMU data to a PDC and then sending the output of the PDC through a secure Ethernet gateway (**Fig. 5**).

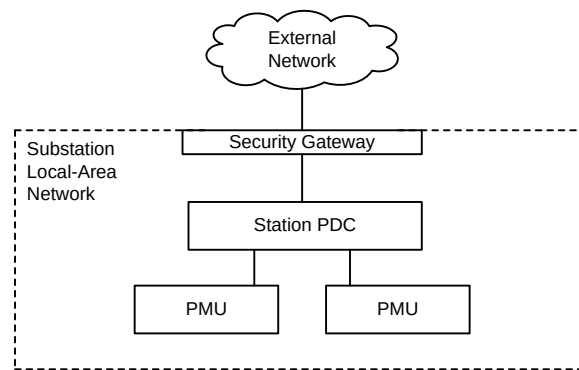


Fig. 5: Multilayer system architecture

This architecture reduces the likelihood for a hacker to get access to, take control of, 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 the system 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 synchronous optical network 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).

6 CONCLUSION

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 electrical quantities and any digital status that can be input into the relay and/or the PMU.
- All of the data are accurately time-stamped and include unique PMU identification as well as a wealth of status bits that ensure that the data received are valid.
- Because IEEE C37.118 is a streaming protocol, information is delivered on a near real-time basis. The message rate is user configurable, allowing a match of the data bandwidth with the bandwidth available.

The IEEE C37.118 protocol could be used to replace existing data collection systems and protocols. Use all of the available information in the IEEE C37.118 message to get the maximum benefit out of these streaming data.

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