SPP Members
PMU Planning Approach

SPP PMU Project Team and Synchrophasor Strike Team

SPP Southwest Power Pool

Revision History

Date or Version Number	Author	Change Description	Comments
10/28/16	Cody Parker	Template setup to address PMU Placement and Priority, cost-estimate approach, CIP approach, and other SST Charter Key Questions[1]	First Draft
11/01/16	Kyle McCraw	Filling in some blanks.	Still rough
11/08/16	Mike Nugent	Added more sections and detail, added purpose statements for each sections.	Second Draft
12/05/16	Mike Nugent	Adding to draft	Second Draft continued
02/16/17	Mike Nugent	Added detail around estimated costs, DDR usage, PMU placement and registration, other areas	Third Draft for SST review. Will continue to add to the document
04/03/17	Mike Nugent	Added detail for CIP Implications.	Draft for SST Face-to-Face review
04/26/17	Mike Nugent	Incorporated feedback from SST face-to-face. Added "PMU System" section and detail to "Systems and Software", commissioning, and PDC sections. Cleaned up some italicized text	Draft for SST review on 4/27
05/23/17	Mike Nugent	Modified "Member Considerations in the Development of a PMU Project" section, disclaimer	Draft for SST review on 5/25/17
12/01/2017	Mike Nugent	Incorporated minor changes requested by SST, updated bandwidth estimates, and removed Draft per SST.	Comments applied per SST approval on 10/12/17.

[1] SST Charter and Key Questions available at https://www.spp.org/spp-documents-filings/?id=61279.

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Overview

Purpose and Scope

The *SPP Members PMU Planning Approach* document should serve as a reference guide for Members that are investigating PMU technology. This guide intends to address topics such as optimal PMU placement, PMU equipment considerations, and communications specifications.

Much of the information in this guide has been obtained from existing research and documentation that will be cited and referenced as needed (see "References"). This document should assist in the research of PMU technology, but will not attempt to replace the breadth of PMU documentation and material available in the public space.

SPP Project Overview

Synchrophasor technology includes a wide array of monitoring, data processing, and wide area visualization systems to help utilities and grid operators better manage the electric grid to improve its reliability. It is focused specifically on providing improved, real-time monitoring of grid conditions, and providing better tools to help diagnose and respond to issues surrounding the intermittent nature of renewable energy sources providing power to the electric grid.

In the near-term, SPP is focused on leveraging existing PMU data along with open source and vendor supplied software to further understand the value this technology can bring to the SPP goal of providing region-wide reliability. The first SPP PMU project is expected to equip SPP with the capability to enhance current operations, after-the-fact event analysis, and system model validation efforts. Additionally, PMU data can assist in real-time situational awareness with measurement based dynamic voltage stability monitoring, detection of oscillatory modes, real-time tracking of phase angles to assess stress of the grid, identifying generator trips, island situations, and enhance State Estimator accuracy.

SPP proposes the implementation of this initiative in three distinct phases. The Phase I project and budget was approved in 2015 and is on track to be completed on time and on budget in 2017. Phase II and III are future projects currently under consideration and may be submitted through the SPP Project Review and Prioritization Committee (PRPC) in the future. Phase III will only be submitted if and when SPP staff feels the systems are serving a critical operational need and as such should be treated as a CIP asset.

- Phase I (approved and underway in 2016)
    - Installation of systems to provide capability to send, receive, and archive synchrophasor data, perform after the fact analysis, deploy real-time analytics engine for use in real-time operations as a non-critical informational tool in 2017.
    - Setup Synchrophasor Strike Team (SST) to engage stakeholders, apply lessons learned, and develop business case for members. See charter[2] for additional details.

[2] https://www.spp.org/Documents/37693/SPP%20SST%20draft%20charter%20033116_v1.docx

  - Support Department of Energy funded Open and Extensible Control and Analytics (openECA) Platform for Phasor Data project where SPP staff will deploy, test, and demonstrate the application being developed.
- Phase II
  - Development of a member facing PMU portal to facilitate collaboration between SPP and members. Enhancing member's access to PMUs throughout the SPP footprint is expected to provide new and enhanced capabilities to all members.
- Phase III
  - Integrate PMU data collection and analytics into SPP's secure data network for use with State Estimator and classifying PMU applications as a critical tool for real-time operations.

The key project activities from 2016 through 2019 and beyond include:

- Develop a 5 year roadmap for use of synchrophasors at SPP
- Establish a robust synchrophasor network
- Work with Members to validate and manage the synchrophasor data
- Develop optimal synchrophasor technology solution for performing analysis and assessment of grid performance based on synchrophasor data
- Educating staff and members on the capabilities and advantages made available by synchrophasor data
- Creating policies and procedures to manage and maintain the synchrophasor network and data storage archives.
- Support stakeholder process of defining the changes needed to integrate synchrophasor monitoring technology into the control room.

SPP is also supporting the DOE-funded FOA-970 project tasked with developing and testing new open source synchrophasor applications with the Grid Protection Alliance along with utilities including OG&E, Virginia Power, BPA, and others. The objective of the Open and Extensible Control and Analytics (openECA) Platform for Phasor Data project is to develop an open source software platform that significantly accelerates the production, use, and ongoing development of real-time decision support tools, automated control systems, and off-line planning systems that (1) incorporate high-fidelity synchrophasor data and (2) enhance system reliability while enabling the North American Electric Reliability Corporation (NERC) operating functions of reliability coordinator, transmission operator, and/or balancing authority to be executed more effectively. This FOA-970 project is a $3M cost sharing initiative with significant deliverables expected in 2017. SPP has committed staff time to deploy, test and demonstrate the applications.

Member Considerations in the Development of a PMU Project

Synchrophasor technology can be a key addition to the toolsets of Transmission and Generation Owners. This technology allows remote facility monitoring, diagnosis, and analysis that isn't possible or easily accomplished with traditional SCADA technology. PMUs may also enhance existing processes, such as power quality analysis, allowing evaluations to be performed more frequently and easily.

Transmission Owners and Generator Owners may find that PMU technology can be used to assist with several NERC standards, including:

- MOD-026-1: Generator excitation control system or plant volt/var control functions (GO applicability)
- MOD-027-1: Turbine/governor & load control or active power/frequency control functions (GO applicability)
    - PMU-based model validation saves money for generation owners (lower plant testing costs, faster identification of plant problems) and transmission owners (improve plant and system models).
- MOD-33-1: Steady State and Dynamic System Model Validation (TO applicability)
    -
- PRC-002-2: Disturbance Monitoring and Reporting Requirements (TO and GO applicability)
    - DDR devices installed per the standard can be networked to stream real-time data, simplifying data gathering for DDR-related events. This also enables the entity to extract real-time value from the DDR device investment.

Synchrophasor technology also enables Transmission and Generator Owners to diagnose and potentially prevent equipment mis-operations before they occur. This can have far-reaching benefits both in the reduction of unplanned outages as well as the potential to minimize equipment damage. There are several potential mis-operations that can be identified through PMU data analysis:

- Generator settings and generator equipment
    - Identify problematic PSS and AVR settings or control malfunctions
    - Identify sources of oscillations, allowing further diagnosis and correction at the generator
- Transmission equipment
    - Identify controller oscillation on HVDC or SVC equipment
    - Spot loose connections as well as PT and CT problems before they fail
    - Monitor sub-harmonics and noise from new equipment
    - Perform transmission-level fault analysis (using 3-phase data)
    - Identify open phases and unbalanced phase currents on breakers (using 3-phase data)
    - Identify capacitor bank switching problems
- Equipment installation and protection
    - Commissioning PSS
    - Verify equipment phasing
    - Monitor system current imbalance
    - Verify system protective device operation

In order to maximize the value and minimize the effort required to adopt PMU technology, it will be important for Transmission and Generations Owners to collaborate and share ideas, use cases, and successes along the way. Sharing actual PMU data, training, and analysis results will also help increase Member's understanding and adoption of the technology. The Synchrophasor Strike Team hopes to continue to promote this collaboration among SPP Members. SPP also plans to share its own analysis results, real-time as well as archived data with Members in hopes of promoting real-time usage, after-the-fact analysis, and model validation. (see *SPP Project Overview).*

PMU Locations

Strategic placement of PMUs is critical for enabling the use of real-time applications and tools. It is recommended that PMU placement be driven by the intended applications that will use the data and the requirements associated with each application.

It is also valuable to install PMUs at locations critical to the grid. This would include EHV substations, critical flow paths, points of interconnection for large plants and intermittent resources, and other unique system locations (dynamic reactive power resources such as FACTS devices, HVDC terminals, arc furnaces, and major system loads). In some cases, it may be possible to install PMUs at adjacent locations and still provide the needed visibility.

PMU Placement Study for Future Installations

Determining optimal placement for PMU devices is important to ensure cost effectiveness and maximum value. SPP performed a PMU placement study based on key information from the Network Model to come up with a ranking of the most important substations for PMU installations.

The PMU placement study used a data-based ranking approach based on several substation characteristics:

- Bus Nominal Voltage
- Generation MW (Capacity and Avg. Actual from EMS)
- Avg. Load MW from EMS
- Total Line Flow In/Out from EMS
- Number of Lines and EHV Lines
- Presence of DC Ties
- SPP Balancing Authority Ties
- Presence of Variable Generation
- Presence of SVCs or Synchronous Condensers
- Flowgate Association
- Total Branch Line Length

The results of the study can be used to prioritize the placement of future PMU installations.

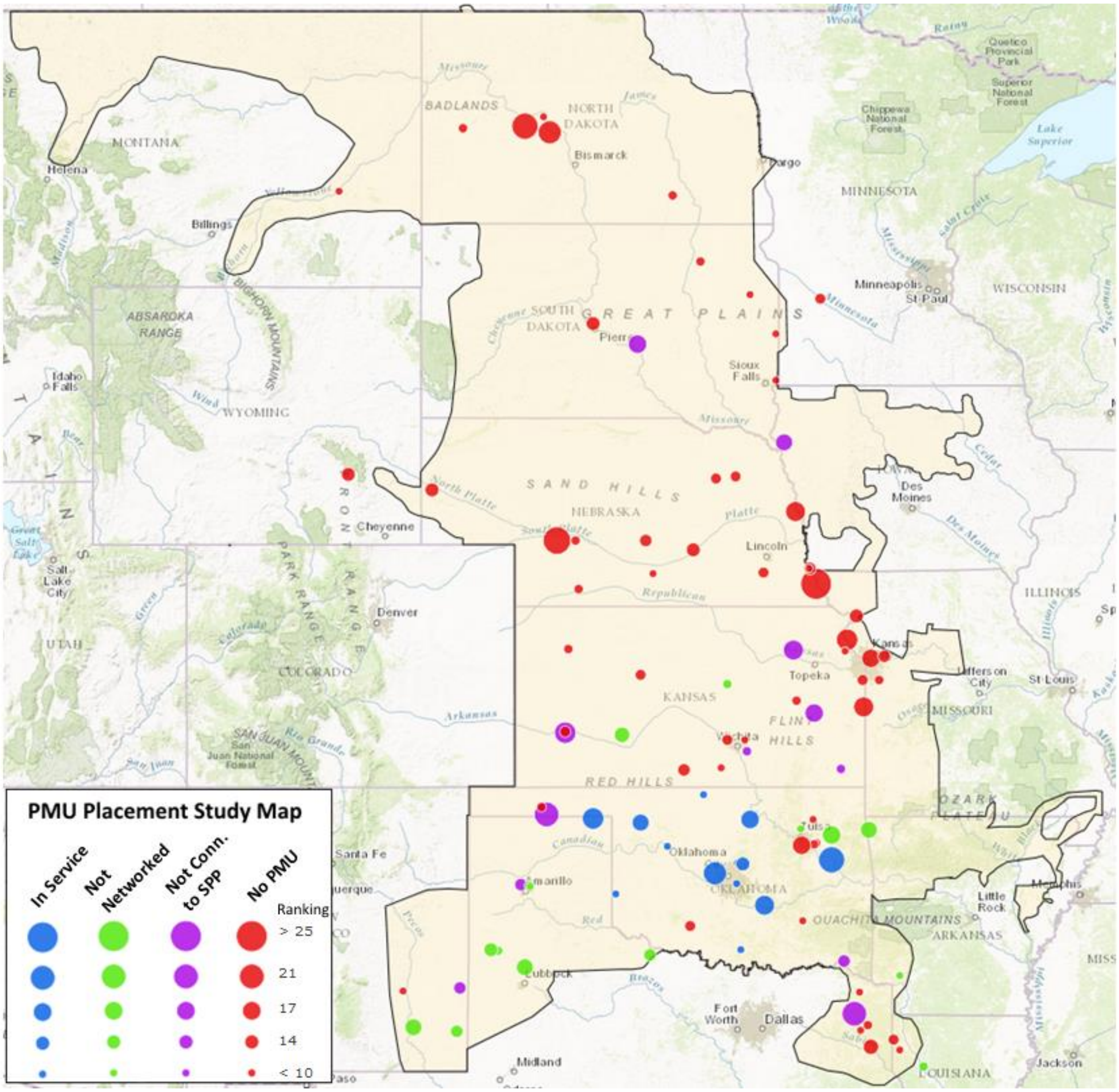

Figure 1: PMU Placement Study Locations by Ranking

PMU Substation Count Breakdown				
Ranking Range	10-14	15-19	20-25	Grand Total
In Service	7	4	2	13
No PMU	48	6	4	58
Not Networked	10	5		15
Not Streaming to SPP	5	5	2	12
Grand Total	**70**	**20**	**8**	**98**

Presentation on the PMU Placement Study can be found in the SST Meeting Materials:
https://www.spp.org/Documents/41483/SST08112016.zip

PMU Registration of Existing Installations

One of the primary goals of Phase 1 of the SPP PMU project is to make use of existing PMU devices already deployed in the field. This will allow SPP and SPP Members to gain experience with PMU data with little to no Member costs incurred. SPP has begun to perform a series of data gathering efforts with the goal of compiling a list of PMU capable devices installed in the field.

The first phase of this effort was completed in Summer 2016, and focused on devices with PMU functionality already enabled. As shown in Figure 1 above, several devices exist in the field but lack communications or PDC's to bring the data back to the control center. Several other devices are networked and streaming data, but have yet to be shared with SPP.

The next phase of this registration effort will focus on PMU-capable (and compatible) devices already installed at substations with existing communications, including DDR devices. These devices would likely require minimal investment to enable PMU functionality (for many PMU-capable devices, a satellite clock and antenna are all that is required to enable PMU functions). Existing communications would allow the data to be transmitted back to the control center with little to no investment. This effort will also focus on gathering specific equipment model information, which will be compared against the list of recommended devices in this document to determine which would be good candidates for PMUs. This registration phase would also seek to gather a list of substations with high-speed networking in-place, with no current PMU-capable devices installed.

The final phase will aim to identify and document critical substations where a PMU would be valuable but doesn't currently exist. This information could be an input for potential new equipment installations in the future. This phase will focus on assisting SPP Members, as needed, with a study of individual substations to evaluate the complexity and cost of networking upgrades, equipment installation, and CIP-related changes necessary to install PMUs.

PMU Installations

Streaming data from substation PMU devices back to the control center requires several key pieces of equipment. The PMU is the central piece, and can be provided as a stand-alone device or as a function within another device, such as a relay or DDR. In many cases, existing digital relays are capable of providing PMU measurements. The next piece of equipment is the satellite clock and antenna which connect to the PMU and provide a highly-accurate UTC time source. PMU measurements are fed either through a substation Phasor Data Concentrator (PDC) or directly to a Regional or Control Center PDC, which time-aligns and processes data from multiple substations before sending to downstream applications or other entities.

PMU System

Although PMU measurements can be recorded locally and retrieved offline, real-time streaming data is needed to realize the full value of PMU devices in the field. A PMU System is needed to enable real-time data to be streamed from substation to control center. The diagram and table below depict three potential PMU System designs for Transmission Owners. Each example represents a different level of PMU data utilization by the TO.

Note: It is assumed that any PMU device installed by a Generator Owner will be streamed back to SPP through the applicable Transmission Owner.

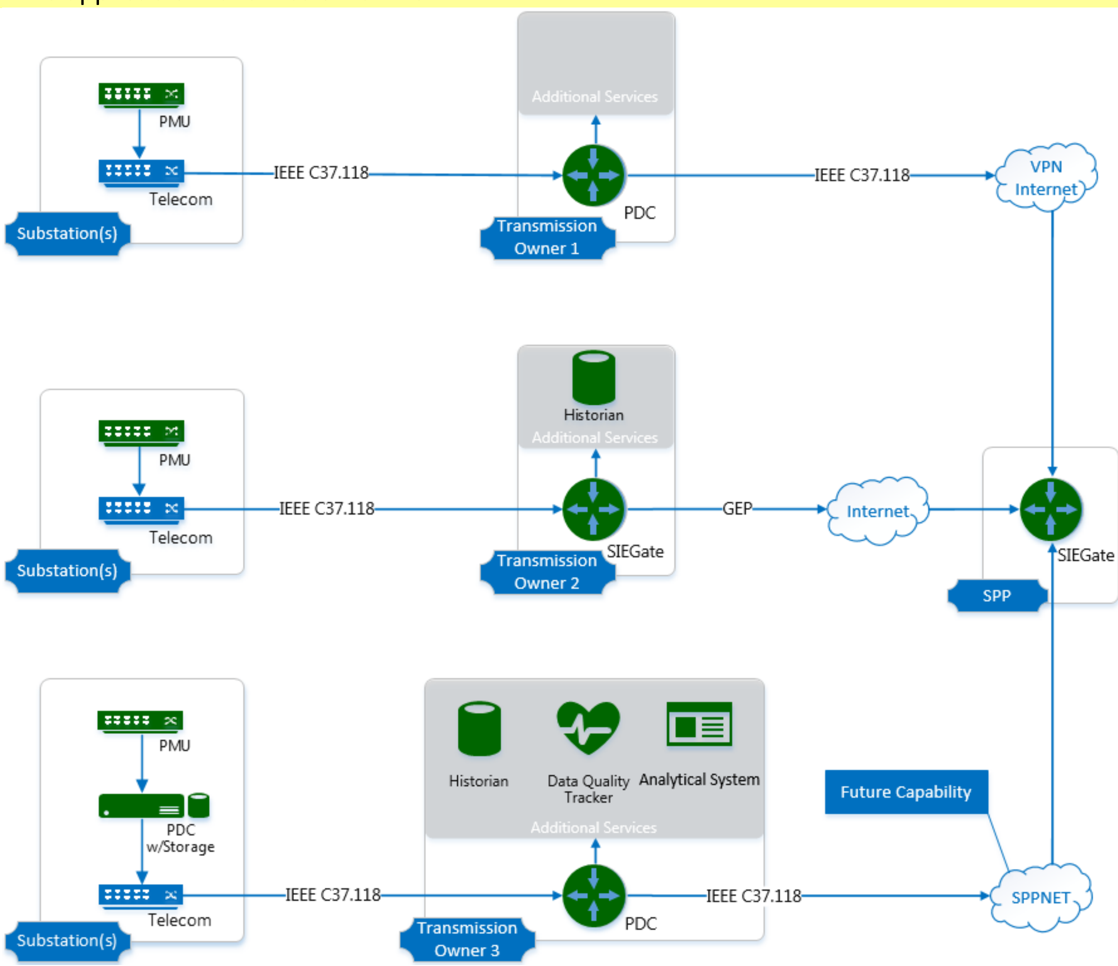

Figure 2: Minimum PMU Architecture for Transmission Owners

Transmission Owner	Level of Involvement	Description
Transmission Owner 1	Very Minimal	Standard PMU with PDC at TOs data center to receive data from substation and a VPN to stream PMU data to SPP.
Transmission Owner 2	Minimal	Standard PMU with SIEGate at TOs data center to receive data from substation and then utilizing SIEGate to stream encrypted PMU data to SPP.
Transmission Owner 3	Advanced	Standard PMU with a PDC for storage at the substation, additional storage at TOs data center, software to perform real-time analytics and post-event analysis, and streaming data to SPP using the secure SPPNet (ICCP network).

Transmission Owner 1 in this example is not making internal use of the PMU data, but has set up a regional PDC to collect and stream data to SPP. This TO is streaming PMU data in C37.118 format, using a VPN tunnel connection for data security.

Transmission Owner 2 is making use of SIEGate, an open-source PDC with built-in security, to collect and stream PMU data to SPP using the native Gateway Exchange Protocol (GEP). This TO is also storing the data in a central historian for offline use and after-the-fact analysis.

Transmission Owner 3 has deployed a substation PDC, allowing for local data recording, in addition to a regional PDC with a central historian. This configuration allows for additional flexibility where local data can be used in the event of downtime of the real-time streaming data. This TO is also making use of PMU analytics software to perform real-time monitoring or after the fact analysis. In this example the TO is streaming data to SPP in a C37.118 format using SPPNET, a dedicated and secure network currently used for ICCP data transfer. This network is expected to be available for PMU data transfer in the future.

PMU Equipment

IEEE C37.118 Standard

The IEEE Synchrophasor standard C37.118 sets minimum requirements that should be achieved by all PMUs. These requirements are intended to assure that the measurements from all PMUs will be comparable under a variety of typical power system operations. The measured values will not be identical due to different measuring methods, so the standard tries to assure that the measurements are the same (comparable) to a level of analysis or observation that would typically be used by a power utility.

The IEEE Standard C37.118-2011 series specifies class of performance (M or P), reporting rates capability, and data representation (polar/rectangular, integer/floating point) that can be used. Most PMUs allow the user to choose the options they want, but some options are fixed by the vendor. If one or another option is needed or preferred, the user should be sure the PMU they select will provide that option. In addition, some PMUs will only output single phase phasors, some only positive sequence, and some both. This also should be determined by the user for what they require. SPP recommends devices that support polar and floating point data.

PMU Device Classes

From IEEE Std C37.118.1-2011:

> 5.5.2 Performance classes
> Compliance with the requirements shall be evaluated by class of performance. This standard defines two classes of performance: P class and M class. P class is intended for applications requiring fast response and mandates no explicit filtering. The letter P is used since protection applications require fast response. M class is intended for applications that could be adversely effected by aliased signals and do not require the fastest reporting speed. The letter M is used since analytic measurements often require greater precision but do not require minimal reporting delay. However these two class designations do not indicate that either class is adequate or required for a particular application. The user must choose a performance class that matches the requirements of each application.

The NERC Reliability Guideline on PMU Placement and Installation recommends M-class PMU devices for oscillation monitoring, as they avoid signal aliasing. P-class devices employ less filtering, which may be beneficial for fault or other types of transient analysis.

PMU Equipment Considerations

This section addresses the various considerations for selecting PMU devices for particular applications. The key is standardization to minimize up-front configuration effort as well as troubleshooting down the road.

Input Support

- Number of Input Phasors:
  Most PMU-capable relay devices support 6 to 12 phasor inputs. 6 input phasors would allow for the collection of 3-phase data from a single transmission line (3 current and 3 voltage phasors). More inputs allow more transmission assets to be monitored with fewer PMU devices. Some DDR devices support up to 64 phasor inputs.
- Sampling Rate:
  PMU devices should support a sampling rate of at least 30 or 60 samples per second.
- Filtering:
  As noted above, P and M class devices employ different levels of filtering. The class of device should be chosen based on the end usage of the data. Typically, M class devices are preferred
- Input Characteristics:
  Input scaling should be configured appropriately to ensure accurate data is recorded under both steady-state and fault conditions. Devices should also support analog and digital values for purposes of reporting device status and other data points.

Satellite Time Input (GPS)

See “Satellite Clock Models Currently In-Use in the SPP Footprint”

Single Phase, Three Phase, or Positive Sequence

Three-phase data is very beneficial for fault analysis as well as analysis of equipment mis-operations. Three-phase data provides maximum resolution for detailed analysis, but requires three times the network bandwidth and storage as compared to positive sequence data. TOs will see the most value from PMU technology using three-phase measurements.

For SPP's particular use cases, positive-sequence data is sufficient and even preferred. Most PMU devices have the option to output positive sequence data, three-phase data, zero-sequence data, or any combination of the above.

Output Capability

- Polar vs. Rectangular:
  Most PMU devices support either data format. SPP prefers polar data.
- Floating-Point Data:
  Devices should support floating-point values, which allow for more accuracy than integer-based data. Integer-based data can be problematic for small-signal and oscillation analysis.
- Local Data Recording:
  Devices should support output of synchrophasor data to local data historians within the substation or device itself. This can be used in lieu of, or as a backup to, streamed data that is stored remotely. Substation PDC's can be used to enable local data recording of any PMU-enabled device.

The dynamic performance of all C37.118-2005 PMUs varies from model to model as this was not defined in the standard. One vendor may have chosen to calculate frequency differently than another one. As a result, during a fault different devices could have different answers for frequency and dF/dT. This is another reason to try to limit the variation of PMU devices installed in the field.

Digital Disturbance Recorders as PMUs

NERC Standard PRC-002-2 requires disturbance monitoring equipment to be installed at critical substations (per criteria outlined in the standard) and specifies that these devices be synchronized to UTC and support data output of at least 30 samples/sec. The standard also specifies that event data from these devices be provided within 30 calendar days of request. The standard became effective on July 1, 2016. According to the PRC-002-2 implementation plan, TO and GO entities are required to be at least 50% compliant with the Digital Disturbance Recorder (DDR) data requirements by July 1, 2020 and fully compliant by July 1, 2022.

It is anticipated that several DDR devices will be installed throughout the footprint to comply with PRC-002-2. Based on the event data turnaround requirements, it is also anticipated that these devices will be networked to allow remote data access. In addition, many of these DDR devices may be set up to monitor equipment that SPP's PMU Placement Study has identified as important for PMU placement.

Many DDR devices on the market today support the output of PMU data in a C37.118 data stream. Care should be taken to ensure that these devices meet the needs of the PMU use cases being deployed (certain DDR devices only support integer value output, which is less than optimal for PMU analysis).

DDR devices tend to support more input channels than PMU-capable relays. For new installations, it may be more cost-effective to install a DDR than several PMU-capable relays, depending on the number of input channels required. This is especially true if the DDR device can also be used to satisfy PRC-002-2 requirements. Another advantage of DDR devices is that they typically have no ability to control the grid, so may have fewer implications for CIP.

Existing Digital Relays as PMUs

Many existing digital relays support PMU data output as a configuration option. Integrating synchrophasor settings into digital relays could enable fast and cost-effective wide-spread deployment of synchrophasors. The only additional equipment needed would be an external GPS antenna to provide a UTC time source.

There are however potential challenges to consider when using existing substation relays for PMU functionality. Many digital relays claim to support the C37.118 protocol, but some are known to present challenges with data quality. This document provides a list of known devices deployed in SPP's footprint with good results. There are also potential CIP concerns with grid-controlling devices connected to a network that uses a routable protocol. For this reason, some in the industry have chosen to install stand-alone PMU devices with no ability to control the grid. Others have connected their relay devices serially, which may create an "air gap" between the device and the routable network. See "CIP Considerations" for more information.

PMU Models Currently In-Use in the SPP Footprint

This section is meant to serve as a guideline for devices that are known to perform well as PMUs. Initial scope was to survey the SPP footprint, but it may be beneficial to expand to others in the US.

Type	Vendor	Model	Description	Notes
PMU	Schweitzer	SEL-351S	Protective Relay	Widely-used
PMU	Schweitzer	SEL-421	Protective Relay	Widely-used
PMU	Schweitzer	SEL-487E	Transformer Protection Relay	
PMU	GE	--	Any PMU-capable IED with version 7+ Firmware	
DDR	Reason Technologies	RPV311	Digital Disturbance Recorder	Only supports UDP (data dropouts possible)
DDR	ERLphase	Tesla 4000	Digital Disturbance Recorder	OGE has selected this DDR as a preferred device going forward
DDR	Ametek	TR-2000	Digital Disturbance Recorder	Not recommended, doesn't support floating point
DDR	Mehta Tech	Transcan	Digital Disturbance Recorder	Higher latency has been observed

Satellite Clock Models Currently In-Use in the SPP Footprint

This section is meant to serve as a guideline for devices that are known to perform well and interact well with PMU devices. Initial scope was to survey the SPP footprint, but it may be beneficial to expand to others in the US.

Vendor	Model	Description	Notes
Schweitzer	SEL-2407	Satellite-Synchronized Clock	
Schweitzer	SEL-2488	Satellite-Synchronized Network Clock	Supports Network Time Protocol
GE	MultiSync 100 1588		

PDC Equipment

PDCs or Phasor Data Concentrators are responsible for collecting, packaging, and "time-aligning" measurements from multiple devices and sending that data on to downstream devices. These devices are typically installed at substations or local regions as well as utility control centers.

Substation PDC Equipment Considerations

The installation of a substation PDC is only necessary for local data recording. A local data recording system allows for additional flexibility where local data can be used in the event of downtime of real-time streaming data. A local data store also allows the TO to locally store more granular or higher-resolution data (up to 120Hz) in the case where the communications network wouldn't support streaming additional data. Substation PDC's/historians should allow for the storage of continuous data as well as event-triggered data, if applicable.

Regional PDC Equipment Considerations

The purpose of the Regional PDC is to collect and time-align all real-time data from field-installed PMU devices before sending on to downstream systems. The Regional PDC also acts as an endpoint for external entities (such as SPP) to connect and stream data, potentially in both directions.

There are many PDC systems available. Many in the industry have chosen a server-deployed software-based solution for scalability reasons. Hardware solutions are also available, but generally limited by the number of supported PMU devices. There are also open-source solutions available, such as Grid Protection Alliance's SIEGate and openPDC who's Gateway Exchange Protocol offers built-in security and compression (see "Bandwidth" section for a comparison of protocol bandwidth requirements). The GEP protocol is planned to be incorporated into a new communications standard as part of the DOE funded "Advanced Synchrophasor Protocol (ASP) Development and Demonstration Project" (DE-OE-859).

Any PDC should support, at minimum, the C37.118-2005 standard for inbound and outbound data. Regional PDC's should also allow users to publish specific PMU devices and signals to external entities.

PDC Models Currently In-Use in the SPP Footprint

This section is meant to serve as a guideline for devices and software that are known to perform well as PDCs. Initial scope was to survey the SPP footprint, but it may be beneficial to expand to others in the US.

Application	Type	Vendor	Model	Description	Utilities Using Device
Substation	Software	GPA	substationSBG	The substationSBG couples the features of the openPDC and SIEGate to form a purpose-built, high-availability data gateway for use in substations. It is both a substation PDC with a local data historian and a phasor gateway to enable the secure, reliable communication of synchrophasor data from the substation to the control center.	
Substation	Hardware	Schweitzer	SEL-3373	Station Phasor Data Concentrator (PDC)	
Substation	Hardware	Schweitzer	RTAC	Real-Time Automation Controller capable of C37.118	
Regional	Software	GPA	openPDC	The openPDC is a high-performance data concentrator platform for managing streaming synchrophasor and other time-series data in real-time.	OGE
Regional	Software	GPA	SIEGate	SIEGate is a security-centric appliance designed from the ground up to reliably exchange the information necessary to support real-time control room operations. SIEGate is a pub/sub technology that exchanges data among devices (such as other SIEGate nodes) using GPA's Gateway Exchange Protocol.	OGE, SPP
Regional	Software	EPG	ePDC	The ePDC is an open, platform independent software system, unlike hardware-based or proprietary legacy PDCs, and is available on Windows or UNIX/Linux systems.	SPP, AEP

PMU Communications

This section should document a high level approach to determine PMU communication requirements to help estimate costs for budgetary purposes. This should include basic network speeds, latency, etc. needed per PMU. This should also include options for consideration along with some pros\cons such as Ethernet, microwave, wireless, and whatever else is out there. Need to survey SPP Members and others in the industry.

Bandwidth

Synchrophasor data is usually communicated at a continuous rate, so there are no bursts and no buffering requirements. The rate is relatively high, with a typical PMU requiring 15-25 kBPS for 30/s measurement reporting rate. A common challenge is usually the need to share circuits with other applications, some of which send data in bursts.

For PMU data, bandwidth is a logical function of the number of monitored phasors per PMU in conjunction with sampling rate.

The IEEE C37.118.2 Synchrophasor Protocol includes standards for PMU communications systems. Data is transmitted in frames that consist of several measurements that correspond to a specific time. Frames are typically sent at a rate of 1 to 60 per second. The data can be transported over asynchronous serial (such as RS232), synchronous serial (such as RS422), or network communications using raw packet transmission or a stacked protocol such as IP. Bandwidth requirements vary depending on the data rate and the amount of data being transmitted.

The following table summarizes the data transmission bandwidth requirements using the C37.118 and Gateway Exchange (GEP) protocols, assuming a TCP/IP network. Three typical situations are presented:

- PMU transmitting 2 phasors (positive-sequence V and I), Frequency and dF/dT analogs and status digital
- PMU transmitting 8 phasors (three-phase and positive-sequence V and I), Frequency and dF/dT analogs and status digital
- DDR transmitting 32 phasors (three-phase and positive sequence V and I for four separate measured terminals), Frequency and dF/dT analogs and a status digital for each terminal

Bandwidth Needed (in kbps) for Data Transmission of Floating-Point Synchrophasor Data Using the C37.118 (un-encrypted) and Gateway Exchange Protocols over TCP/IP

Protocol	c37.118	GEP	c37.118	GEP	c37.118	GEP
# Of PMU @ Data Rate (Frames/Sec)	2 Phasors, 2 Analog, 1 Digital (PMU Pos. Seq. Data)	2 Phasors, 2 Analog, 1 Digital (PMU Pos. Seq. Data)	8 Phasors, 2 Analog, 1 Digital (PMU 3-Phase + Pos. Seq. Data)	8 Phasors, 2 Analog, 1 Digital (PMU 3-Phase + Pos. Seq. Data)	32 Phasors, 2 Analog, 4 Digital (DDR 3-Phase x 6 Devices)	32 Phasors, 2 Analog, 6 Digital (DDR 3-Phase x 6 Devices)
1 PMU @ 30	32.8	8.6	44.1	23.4	90.5	88.6
5 PMU @ 30	66.6	43.1	122.8	116.9	396.1	443
10 PMU @ 30	108.8	86.1	241.9	233.8	788.4	885.9
50 PMU @ 30	508.1	430.7	1153.1	1168.9	3865.3	4429.7
1 PMU @ 60	65.6	17.2	88.1	46.8	180.9	177.2
5 PMU @ 60	133.1	86.1	245.6	233.8	792.2	885.9
10 PMU @ 60	217.5	172.3	483.8	467.6	1576.9	1771.9
50 PMU @ 60	1016.3	861.3	2306.3	2337.9	7730.6	8859.4

Table values calculated using: http://www.gridprotectionalliance.org/docs/products/gsf/GEP-bandwidth-estimator.zip. The calculator also includes estimates for transmitting data over serial.

Data encryption will increase bandwidth requirements, potentially by a factor of 50-150% (assuming a PDC to PDC data transfer over a VPN connection).

Latency

Typical substation PDC to control center links will have 20-50ms of latency. Most latency is introduced by error detection, re-transmission, extra decode-encode points when systems are merged, and changes in data rates. This can add up to 100's of milliseconds.

Latency can become a real issue when considering PDC wait times. Excessive latency from a particular PMU or PDC can result in the measurements from those devices being dropped completely. This often happens intermittently and can be caused by other congestion on the network.

Variable waiting and processing delays in data collection systems can increase overall latency to several seconds, which can have an impact for real-time operations analysis tools. Utilities should design systems to minimize these delays as much as possible.

Reliability/Quality of Service (QoS)

In routable telecommunication networks, Quality of Service is the ability to provide different priority to different applications, users, or data flows, or to guarantee a certain level of performance to a data flow. Quality of Service can be important in highly-utilized networks with application-specific performance requirements.

PMU data is often transmitted back to the control center on a network sharing traffic with other systems or devices at the substation. Depending on the available bandwidth, network congestion from other devices or data flows may have a detrimental impact on the PMU data stream, resulting in high latency and potential data loss.

An example of this would be a PMU that is streaming data over a corporate network which is also used by technicians to download Digital Disturbance Recorder (DDR) data. Without proper QoS configuration, the PMU data could be dropped completely while a large DDR file transfer is taking place.

Proper Quality of Service configuration can improve PMU data uptime and reduce the potential for data quality issues down the road.

PMU Data Storage

There are several vendor-provided and open-source historian tools designed for PMU data storage. SPP has tested the PMU data storage capabilities of both Grid Protection Alliance's OpenHistorian and Electric Power Group's RTDMS database. Overall, SPP found that OpenHistorian is about 3.7 times more efficient than RTDMS. OpenHistorian uses a custom storage mechanism while RTDMS stores raw binary data in a SQL database. The storage estimates below are based on SPP's testing.

System	Storage Mechanism	Average Data Storage per PMU (+ Sequence)	Average Data Storage per Signal (+ Sequence)	Average Statistics Storage per PMU (+ Sequence)
OpenHistorian	GSF SNAPdb archive files	73MB per Day	7.15MB per Day	1.45MB per Day
RTDMS Database	SQL Server Database BLOBs (binary data)	268MB per Day	26.2MB per Day	3.06MB per Day

The Grid Protection Alliance bandwidth estimation spreadsheet also includes a binary storage calculator which produces results similar to the RTDMS database estimates above: http://www.gridprotectionalliance.org/docs/products/gsf/GEP-bandwidth-estimator.zip

Retention

SPP's current plan for Phase 1 is to retain 1 year of online full-resolution data in OpenHistorian. After 1 year, data will either be deleted or moved to a secondary storage location for retrieval if needed at a later time. OpenHistorian is flexible enough to allow archive files to be stored in multiple locations, and easily moved.

Another option for data retention is down-sampling data to a lower resolution after a certain period of time. Some entities may choose to down-sample older data to 1 sample/second or lower to minimize long-term storage impacts. The caveat of this approach is that down-sampled data cannot be used for analysis that requires high-resolution data, such as oscillation or fault analysis.

PMU Data Validation/Commissioning

Given the need for good quality data, it is important to ensure that newly installed or configured PMU devices are set up and tested properly before technicians leave the substation. This will limit the need for technicians to return to the substation for additional adjustments. The primary focus of PMU data validation and commissioning is the PMU device itself, as well as the instrumentation transformers used to meter the voltage and current quantity inputs.

While configuring the PMU device, it is important to ensure that output measurements are correctly identified and labeled, input scaling is correct, and that data output is operational.

After installing and configuring the PMU device, it is important to perform the following tests:

1. Check that the clock used for synchronization to UTC is on time and locked on GPS time. Check that the PMU correctly indicates when time is locked and that the lock is steady.
2. Confirm that the phasor measurement magnitudes are within 1% of input levels. Also confirm voltages are within 1% + 1kV and currents within 1% (Above 50 Amps) of comparable substation measurements.
3. Confirm that the phasor measurement angle differences are within 1 degree of corresponding input signal angle differences. Also confirm the angles with comparable measurements in the substation.
4. Confirm that analog measurements are within 5% of other measuring devices in the substation.
5. Confirm that digital status measurements report the correct Boolean state.

After completion of the field installation, technicians at the central office should collect measurements from the new device and compare those outputs to SCADA or other sources of metering at the substation. The PMU data stream should be monitored for a period of time to ensure that excess latency or data dropouts are not occurring. Any necessary corrections should be made before streaming the data on to SPP.

Once the data for a new device is streamed to SPP, SPP technical staff will perform another series of verifications, including:

1. Reasonability check of phasor quantities
2. Compare voltage angles relative to State Estimator-calculated values
3. Compare power flow and voltage magnitudes to SCADA values
4. Monitor over a window of time for staleness and data dropouts

(Note: For additional methods and detail on PMU device commissioning, see MISO's "PMU Installation and Configuration Requirements" document)

PMU Installation Best Practices

The best practices below for PMU installations are based on experiences and advice from others in the industry.

The cost of the PMU itself is small compared to the costs of installation, communications and security. Some ways to save on PMU installation costs:

- Look for points where one set of PMUs can serve multiple applications
- Use only one model of PMU or turn on PMU functionality within already-installed, late-model, consistent-type digital relays.

- Figure out security, installation practices, settings, etc. and develop checklists and standard practices for everything. Train crews on this (and use same crews) before they go out into the field.
- Pre-fab PMU racks before going out into the field.
- Perform PMU and communications installation when the substation will be worked on for other reasons.
- Have expert support staff (PMUs, IT, engineering) available for phone and on-line support to crews during every installation.
- Standardize and institutionalize PMUs and PDCs into transmission practices (including substation upgrades and new builds).

PMU Cost Considerations

There are many factors that affect the total cost of new PMU installations. These include variances in communications availability, cyber-security considerations, and substation design standards. It is difficult to come up with a one-size-fits-all cost estimate for PMU systems, so this section presents general cost ranges broken down for each major component. The cost of communications is the hardest to estimate, as there are so many variables that this must really be analyzed on a case-by-case basis.

Major Factors Affecting Substation PMU Installation Costs

- **Communications**: Potentially the largest factor in the PMU cost equation. For substations without existing high-speed data networks, the cost of networking can range widely depending on CIP requirements, remoteness of the substation, network availability, and bandwidth requirements.
  - See "PMU Communications"
- **Cyber-Security**
  - See “CIP Considerations”
- **Installation Labor**
  - See “PMU Installation Best Practices”
- **Equipment**
  - PMU
    - For standalone installs, a PMU-capable device, satellite clock and antenna
    - For existing relays, a satellite clock and antenna
  - Substation PDC – Optional, but required for local data recording. Software solutions require a substation PC.
  - Network Equipment – Routers, firewall devices, etc. as required. The costs and complexity vary depending on CIP requirements and eventual use of the data (i.e. if it will be used for 15-minute operational decisions).

PMU Cost Estimates

The 2014 DOE Smart Grid “Factors Affecting PMU Installation Costs” study details the cost of PMU installation reported by each of the project participants. In this report, the average overall costs per PMU (cost of procurement, installation, and commissioning) ranged between $40,000 and

$180,000. The large range in cost is mostly attributed to the amount of networking upgrades needed for each PMU installation.

It is noted that not all PMUs, or the infrastructure required to support them, are equivalent. Simple “cost per PMU” calculations do not reflect differences among utilities in required phasor data concentrators, communications infrastructure upgrades, applications costs, staff training needs, and physical substation constraints to installing PMUs. The PMU device itself can vary in complexity, although the device cost alone is usually not significant; generally, PMU device costs were found to be approximately 5% of the installed cost.

Another caveat of the “cost per PMU” calculation is that the incremental addition of PMUs at a substation does not result in a linear cost increase. Generally, the first PMU installed and commissioned at a substation is the most expensive, as this installation would also involve networking, security, and other supporting systems. Additional PMUs at this same substation would incur a much lower overall cost as the supporting systems are already in-place.

PMU System Cost Breakdown

The diagram below provides an overview of cost estimates for the various components of a PMU System. More detail on each component is provided below.

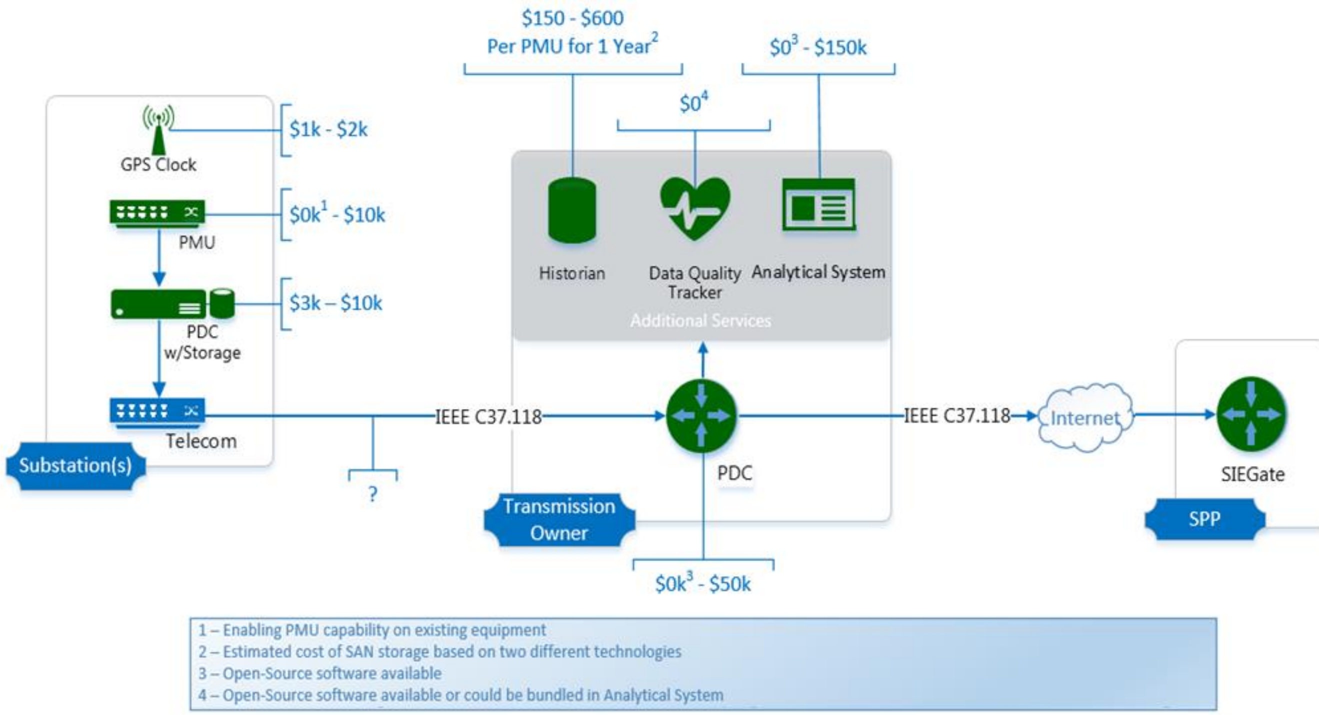

Figure 3: Estimated Cost Breakdown of PMU System

Estimated Substation-Level Costs

Equipment-Only Costs

- PMU Device – New PMU-capable relays range from $5,000 - $10,000. Enabling PMU functionality in an existing device can be done with no hardware cost
- Satellite Clock – Usually only one needed per substation. $1,000 - $2,000

- Substation PDC – Optional. $3,000 - $10,000 depending on software or hardware solution and vendor. For software solution, minimal cost includes a substation-hardened PC and assumes open-source software.
- Local Storage – Optional. Costs depend on retention and backup requirements.
- Networking Equipment – Costs vary depending on security requirements.

Installation Types

- Upgrade of a single existing relay, including satellite clock install, networking, testing, and configuration
- Installation of new PMU-capable relay, including satellite clock install, testing, and configuration
- Installation of DDR device including testing and configuration
- Installation of routing/network equipment in a substation that did not previously have it

Networking Costs

- If existing high-speed network is in-place, even if intended for corporate usage, that network can be utilized to transmit synchrophasor data. It may be necessary to isolate the PMU traffic through a more secure channel. More information in “CIP Implications” section
- For new network installs, costs can vary widely depending on multiple factors. A good approach may be to estimate based on proximity to other networked substations as well as proximity to large towns or cities. In the end, networking costs will vary on a case-by-case basis.

Estimated Business Costs

In addition to installation costs, SPP Members who intend to use synchrophasor data for their own business uses and analytics should consider the staff and technology required.

Systems & Software

- Regional PDC – The regional or control center PDC is generally a server-deployed software solution, but can be managed with a hardware solution depending on the amount of PMUs deployed. Open-source software is available, as well as a range of vendor-provided software and hardware solutions. See “PDC Models Currently In-Use in the SPP Footprint” $0-$50,000
- Central Historian (optional) – A central historian is needed for a TO to retain PMU data for after-the-fact analysis. In general, expect $150-$600 per PMU per year for positive-sequence data storage. Three-phase data storage will be 3 times that cost. This is based on estimated SAN storage costs ($6,000/TB) figured for each storage technology listed in “PMU Data Storage.”
- Analytical Software (optional) – Analytical software can allow TO’s to monitor PMU analysis results in real time as well as perform post-event analysis. There is a wide range of PMU analytical software available from multiple vendor and research-based providers. There is also open source analytical software available. The cost is largely dependent on the provider as well as the intended end use. $0-$150,000

Staffing

- SPP’s initial budget for the SPP PMU Project was for 2 additional FTEs; one Engineer and one IT Support.

- TOs may not necessarily need to increase headcount to accommodate PMU technology. However it is suggested to have at least one person tasked with using and getting value out of the synchrophasor data. The tasks for this individual could involve developing new business processes, integrating synchrophasor data with existing processes, developing or making use of vendor-supplied analytics, and staying abreast of synchrophasor research in the industry.
- TOs should also consider the additional support needs of PMU data. This shouldn't be much different than existing SCADA support, but will require someone to monitor the quality of the data and take corrective action when something is wrong.
- From an Engineering perspective, it would be beneficial for the individual(s) responsible for using and analyzing the PMU data to have a System Protection, dynamics, operations, or planning background.

CIP Considerations

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CIP version 5 went into effect April 1, 2016 (high and medium impact) and April 1, 2017 (low impact). Each individual entity subject to NERC CIP Reliability Standards is responsible for complying with those standards.

General Guidelines

- BES Cyber Systems inside substations are divided into Medium Impact BES Cyber Systems and Low Impact BES Cyber Systems. A substation can have both Medium and Low Impact BES Cyber Systems. An Electronic Security Perimeter must surround the Medium Impact BES Cyber Systems that are connected to a routable network. No ESP is required to surround Medium Impact BES Cyber Systems connected serially, nor around any Low Impact BES Cyber Systems.
- If a PMU device is within an Electronic Security Perimeter, then the PMU is a Protected Cyber Asset, subject to all of the applicable requirements of CIP-003 through CIP-011.
- The categorization of a PMU with control capability as a Medium or Low Impact BES Cyber Asset will depend entirely on the Facility that is being controlled by the PMU device. The device, without regard to its PMU capability, needs to be evaluated against the Impact Rating Criteria to determine the categorization. See CIP-002-5.1a

Additional Guidelines

- Phasor data is not presently used for Bulk Electric System (BES) control purposes or automated actions.
- Phasor data is not presently being used to make real-time operational decisions within a 15-minute time window.

- Some PMU data is serially transmitted; some may be transmitted via Ethernet. IEEE C37.118 describes a data structure that may be transmitted serially or routed over a network connection.
- A PDC and/or PMU transmitting data on a communications network with other BES Cyber Assets may dictate the PDC and/or PMU be treated in a similar fashion. More detail in the matrix below.

Reference CIP Applicability Matrix (Informational)

Possible CIP Implications of Installing PMU's in CIP Medium Systems; Assuming PMU Data NOT Used for 15-Minute Opeional Decisions				
	New stand-alone PMU or DFR device with no system control (**assumed to be not classified as a BES Cyber System**)		Enabling PMU Function in Existing Relay with system control; OR New PMU device with system control (**classified as a BES Cyber System**)	
	Equipment Impacts	Documentation Impacts	Equipment Impacts	Documentation Impacts
CIP Medium: No existing routable traffic crossing the BES Cyber System boundary	CIP-005 should be inapplicable if the PMU device can be installed on a network that is isolated from the ESP network inside the substation. Routers or firewalls may be required to ensure this isolation	Assuming the device itself is not classified as a BES Cyber System, no further documentation required. If the PMU is connected to the same network as any Medium-Impact BES Cyber System (inside an ESP), it becomes a Protected Cyber Asset and is subject to CIP standards.	If the PMU-enabled device performs any control functions (e.g., breaker control), then the PMU is a BES Cyber Asset, subject to the CIP Standards. Device must be connected to the substation ESP. Routers, firewalls, or other equipment may be required to establish an Electronic Access Point (EAP) for external routable traffic. Additional equipment may be required to establish an Intermediate System for Interactive Remote Access.	CIP-005 already in effect. Per CIP-005, all external routable connectivity must be through an Electronic Access Point (EAP). All inbound/outbound electronic access must have documentation
CIP Medium: Existing routable traffic crossing the BES Cyber System boundary	Same as Above	Same as Above	Minimal. Device must be connected to the substation ESP. Assuming an ESP network and Electronic Access Point systems already exist at the substation, the PMU would need to be installed on that network and configuration changes be made to allow routable traffic to the PMU	Same as Above

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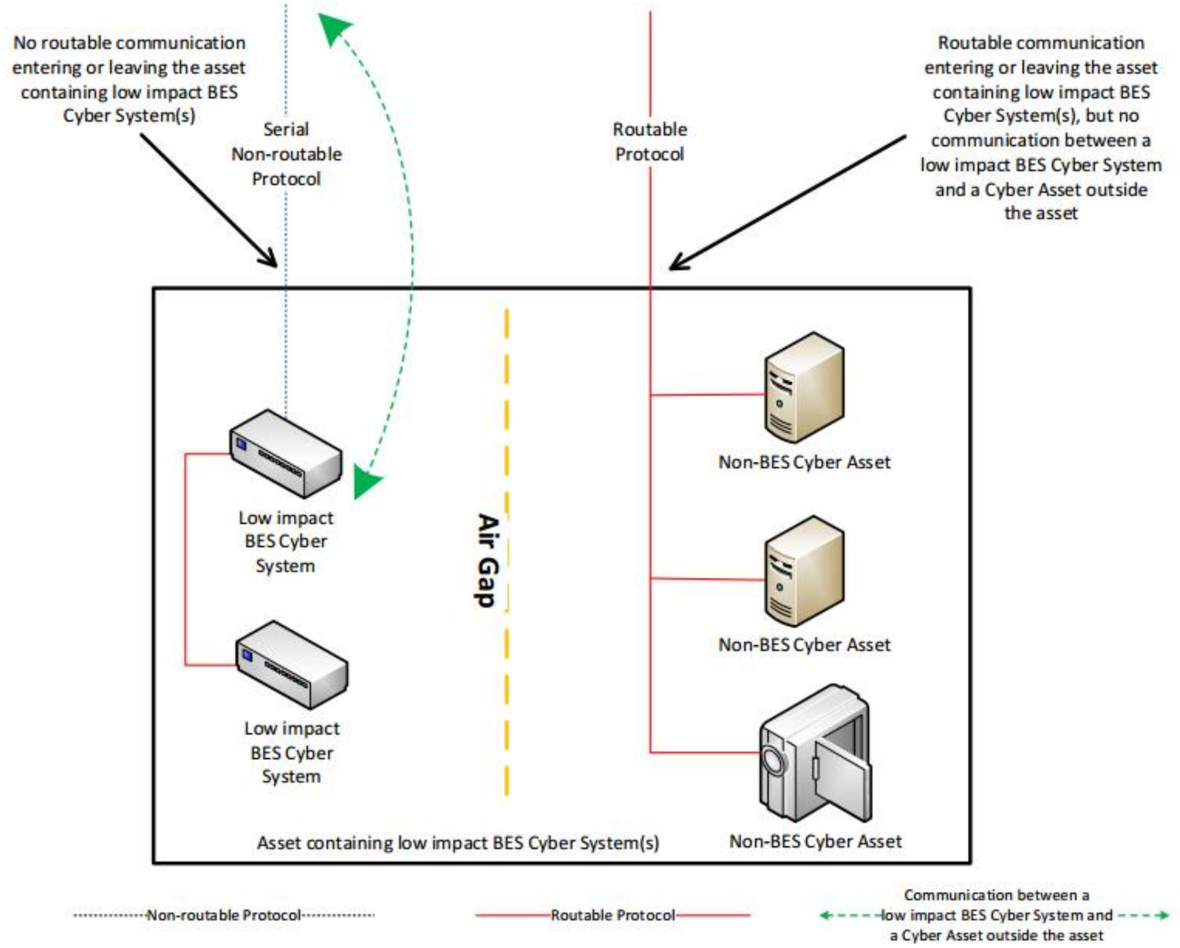
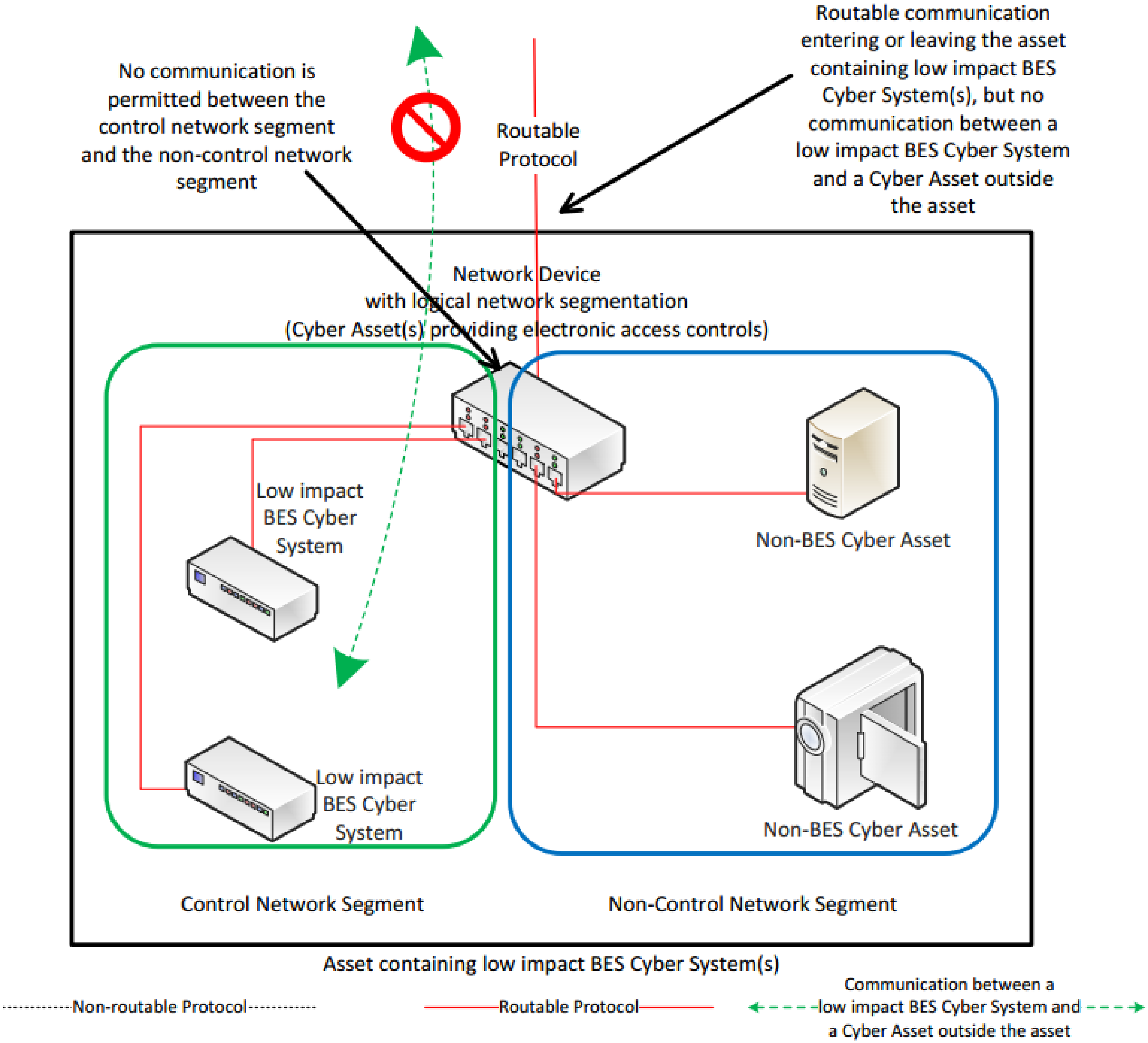
Possible CIP Implications of Installing PMU's in CIP Low Systems; Assuming PMU Data NOT Used for 15-Minute Operational Decisions				
	New stand-alone PMU or DFR device with no system control (**assumed to be not classified as a BES Cyber System**)		Enabling PMU Function in Existing Relay with system control; OR New PMU device with system control (**classified as a BES Cyber System**)	
	Equipment Impacts	Documentation Impacts	Equipment Impacts	Documentation Impacts
CIP Low: No existing routable traffic crossing the substation boundary	Electronic Access Control requirements per CIP-003-7 should be inapplicable if the PMU Device can be installed on a network that is "air-gapped" or logically isolated from the BES Cyber System network (see Reference Model 8 and 9 in CIP-003-7 Supplemental Materials).	If, in the absence of the PMU, there are no Low Impact BES Cyber Systems in the substation communicating outside of the substation with routable protocol (e.g., with the Control Center), then the introduction of the PMU will change the view to one where there is routable communication crossing the asset boundary. The entity will need to demonstrate that the routable communication is isolated from the Low Impact BES Cyber Systems. In this scenario, none of the requirements of CIP-003-7 will be applicable	Routers, firewalls, or other Electronic Access Control systems may be required to control inbound/outbound electronic access to the BES Cyber System(s). Refer to CIP-003-7 Supplemental Material Reference Models for more guidance.	Substation will become subject to CIP-003-7. This may include creation of a Cyber Security Plan, a Security Awareness Program and a Cyber Security Incident Response Plan for the Low impact BES Cyber Systems. Entity must evaluate and demonstrate compliance with Electronic Access Control requirements.
CIP Low: Existing routable traffic crossing the substation boundary	Electronic Access Control requirements per CIP-003-7 should be inapplicable if the PMU Device can be installed on a network that is "air-gapped" or logically isolated from the BES Cyber System network (see Reference Model 8 and 9 in CIP-003-7 Supplemental Materials)	None. Existing Routable network indicates that CIP-003-7 compliance is already in effect	Minimal. Assuming a BES Cyber System network and applicable Electronic Access Control systems already exist at the substation, the PMU would need to be installed on that network and configuration changes be made to allow routable traffic to the PMU	None. Existing Routable network indicates that CIP-003-7 compliance is already in effect

Models 8 & 9 from CIP-003-7:



Reference Model 8 – Physical Isolation and Serial Non-routable Communications – No Electronic Access Controls Required. In this reference model, the criteria from Attachment 1, Section 3.1 requiring the implementation of electronic access controls are not met. This reference model demonstrates three concepts:

1. The physical isolation of the low impact BES Cyber System(s) from the routable protocol communication entering or leaving the asset containing the low impact BES Cyber System(s), commonly referred to as an 'air gap', mitigates the need to implement the required electronic access controls;
2. The communication to the low impact BES Cyber System from a Cyber Asset outside the asset containing the low impact BES Cyber System(s) using only a serial non-routable protocol where such communication is entering or leaving the asset mitigates the need to implement the required electronic access controls.
3. The routable protocol communication between the low impact BES Cyber System(s) and other Cyber Asset(s), such as the second low impact BES Cyber System depicted, may exist without needing to implement the required electronic access controls so long as the routable protocol communications never leaves the asset containing the low impact BES Cyber System(s).



Reference Model 9 – Logical Isolation - No Electronic Access Controls Required In this reference model, the criteria from Attachment 1, Section 3.1 requiring the implementation of electronic access controls are not met. The Responsible Entity has logically isolated the low impact BES Cyber System(s) from the routable protocol communication entering or leaving the asset containing low impact BES Cyber System(s). The logical network segmentation in this reference model permits no communication between a low impact BES Cyber System and a Cyber Asset outside the asset. Additionally, no indirect access exists because those non-BES Cyber Assets that are able to communicate outside the asset are strictly prohibited from communicating to the low impact BES Cyber System(s). The low impact BES Cyber System(s) is on an isolated network segment with logical controls preventing routable protocol communication into or out of the network containing the low impact BES Cyber System(s) and these communications never leave the asset using a routable protocol.

Summary

In summary, it is up to the individual PMU and communications network owner to determine specifically whether and how the NERC CIP standards apply, particularly if the PMU data is used for operational purposes (based on the NERC Functional Model descriptions for "real-time" operations, including situational awareness). If Synchrophasor data is being relied on to make real-time operational decisions, then the PMUs themselves would be considered no differently than other relays or RTUs providing similar operational data to an operator. Refer to https://www.naspi.org/File.aspx?fileID=533 for further details on this topic. The industry-recommended best practice is to proactively design and implement installations that build in a basic level of CIP protection that can be upgraded as the synchrophasor data moves into real-time operational usage.

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