Reference Document for micro-PMU Installation

ARPA-E Plus-Up Project Award # DE-AR0000340, Milestone 1.3.2, Subtask 1.33
Draft March 23, 2018

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This manual is a living document, intended to help utilities and researchers in the planning and installation of networks of micro-phasor measurement units (μPMUs) on distribution circuits. It addresses practical barriers and concerns that can be encountered in setting up a network of μPMUs on distribution circuits, as well as issues that arise in maintaining a back end for data storage and analytics. It further discusses the impact of installation location and related limitations, such as instrument transformer error and availability of three-phase voltage and current measurements, on suitability for various analytic applications. It also contains a collection of specific advice and lessons learned from the ARPA-E funded "Micro-Synchrophasors for Distribution Systems" project carried out by researchers and distribution system operators at UC Berkeley (UCB), Lawrence Berkeley National Laboratory (LBL), Power Standards Laboratory (PSL), and a number of partner utilities.

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Introduction to the µPMU System

Synchrophasors are synchronized measurements of voltage and current magnitude and phase angle that give grid operators insight into the state of the grid. Compared to conventional sensor measurements such as SCADA, synchrophasors offer higher precision and accuracy, improved time resolution and synchronization across locations. This information is only increasing in importance as operators and planners must manage the increasing penetrations of variable generation and controllable energy resources. Historically, most instrumentation in the grid, including the phasor measurement units (PMUs) that measure synchrophasors, has been installed at the transmission level. However, improvements in situational awareness are also critical in distribution systems, where the majority of faults occur and where distributed energy resources are increasingly being connected. Therefore, while sensing in distribution systems is challenging compared to transmission—the signals of interest are smaller in magnitude and the number of nodes is much greater—applying synchrophasor technology to the distribution tier is also of interest.

The micro-PMU (µPMU) is a phasor measurement unit designed specifically for applications in distribution circuits. It is built on the PQube 3 power quality recorder from Power Standards Lab (PSL), which measures voltage and current waveforms with 512 samples per cycle. In µPMU mode, the device reports a phasor (magnitude and angle) describing each waveform, with two samples per cycle or 120 samples per second. GPS time stamping is used to synchronize the phasor measurements across locations. The µPMU time stamping has nanosecond-level precision and microsecond-level accuracy using GPS. This allows the µPMU network to measure the phase differences on the order of hundredths of a degree that are typical in distribution circuits, which are too small to be measured with transmission PMUs. Specifications for the µPMU device are given in [1].

The main physical components of the µPMU system are:

- µPMU itself
- GPS receiver
- Ethernet connection, or cellular modem and antenna
- Potential and current transformers, if needed
- Enclosure for hardware
- Server for data network, either locally or in the cloud

Planning and executing the installation of a µPMU system involves a number of steps and considerations. At a high level, these steps are:

- Selecting the locations where each µPMU will be installed, given constraints such as ease of access, phases available, presence of potential and current transformers and their accuracy, and proximity to devices of interest on the circuit
- Selecting local or cloud servers for data hosting
- Selecting the data communication method (wired or wireless), and selecting an appropriate modem and antenna if wireless communication is chosen
- Installing the µPMU, GPS and communication hardware

- Configuring the network and database to manage the data

This manual will present options for each of the choices listed above, along with their advantages and disadvantages in terms of ease of use and suitability for the various applications of μPMUs.

μPMU Hardware and Peripherals

Communications and Antennas

Traditional mechanisms for remote communications are available for data transfer from the μPMU, including ethernet and cellular 3G or 4G modem. Setting up and maintaining the communications will likely require significant effort and expertise. Particularly if wireless communication via cellular modem is selected, tasks and issues include (but are not limited to) modem hardware selection, remote access, modem configuration, modem software updates, and carrier profile updates.

Cradlepoint modems have been used with the μPMUs in past installations and continue to be the recommended type. In particular, the IBR600 series (IBR650B or IBR650LE) are recommended. WiFi is not required for the modem, since it will be connected directly to the μPMU with an ethernet cable. If GPS is desired on the modem (in addition to the GPS already on the μPMU), such as for absolute timing checkpoints along a control path, then the recommendation is the IBR650C, which includes passive GPS.

In addition to the modem itself, modem antennas are an important design choice. Options include:
(a) “Rabbit-ear” antennas that come included with Cradlepoint modems. These are appropriate for indoor use with good cell signal.
(b) “Salt shaker” style antennas, which have a small form factor and acceptable performance in many urban and semi-rural areas. These are the default choice with PSL enclosures.
(c) Directional antennas, which provide the best performance: fewest dropped packets and highest reliability, especially in areas with questionable cellular coverage. Their large form factor may be impractical to fit at some installations, or undesirable for aesthetic reasons.

Manual retrieval by USB drive or SD card is also possible in case of communications failure. Several weeks worth of data are stored on the μPMU itself in a circular buffer.

Physical Protection

We recommend purchasing rugged enclosures from PSL that protect the μPMU and peripherals from the elements (rain, dust, fauna) and ensures safe outdoor installations. Indoor or sheltered installations can use less rugged enclosures, or none at all if the area is secure.

An enclosure will house and protect the µPMU, modem, breaker, and power supply for the µPMU and modem. The GPS receiver needs clear view of the sky and will be external to any enclosure. Modem antennas are also external. For indoor installations, including metal sheds, consider wiring requirements, roof penetrations etc. for GPS receiver and modem antenna.

Power and Wiring

Choices of wiring and power supplies for the µPMU and peripherals depend on the voltage levels available at the installation site and whether convenience outlets are present. For example, while the µPMU itself can support input voltages up to 690 V for measurement, an AC/DC converter and in some cases also a transformer are needed to produce the 12V DC required by the modem. Sample block diagrams for three different installations are shown below.

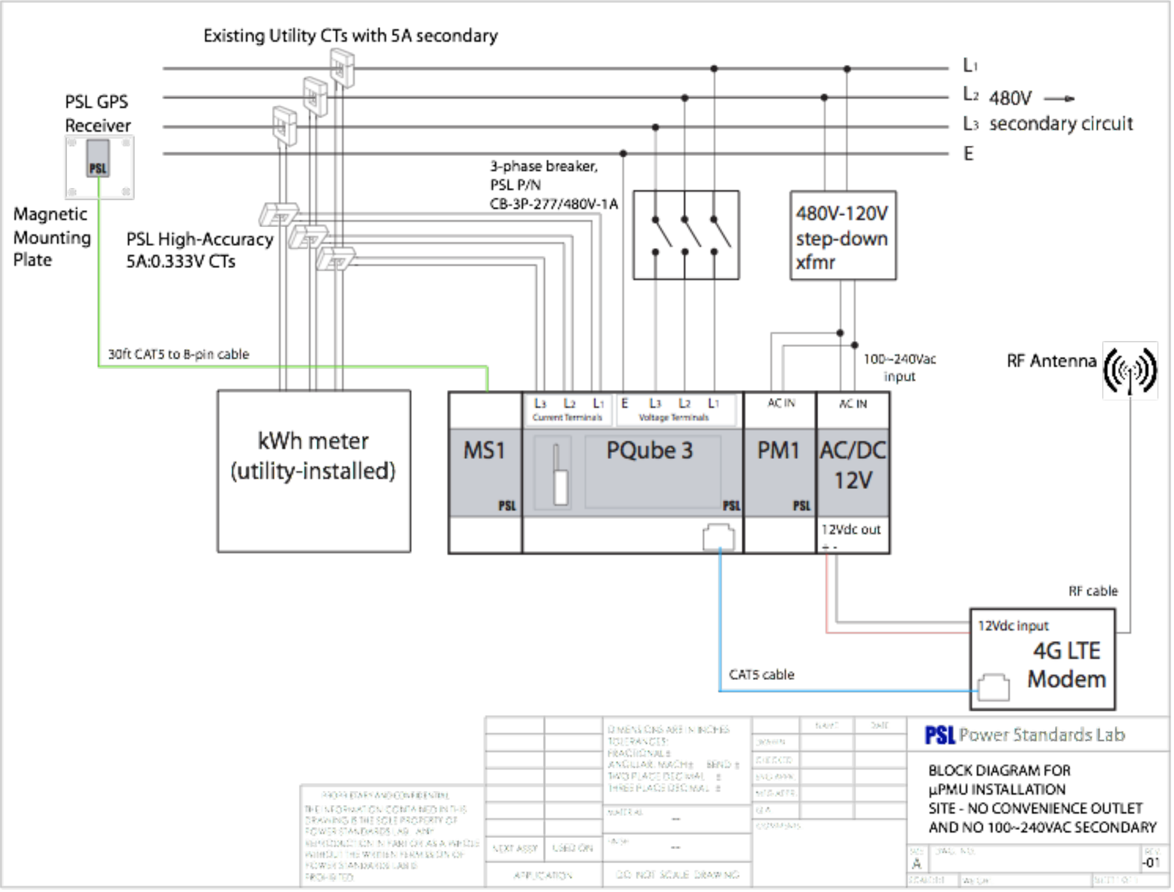

Figure 1. Block diagram for µPMU installation on 480V secondary circuit at a site with no convenience outlet. Courtesy Power Standards Lab (www.PowerStandards.com).

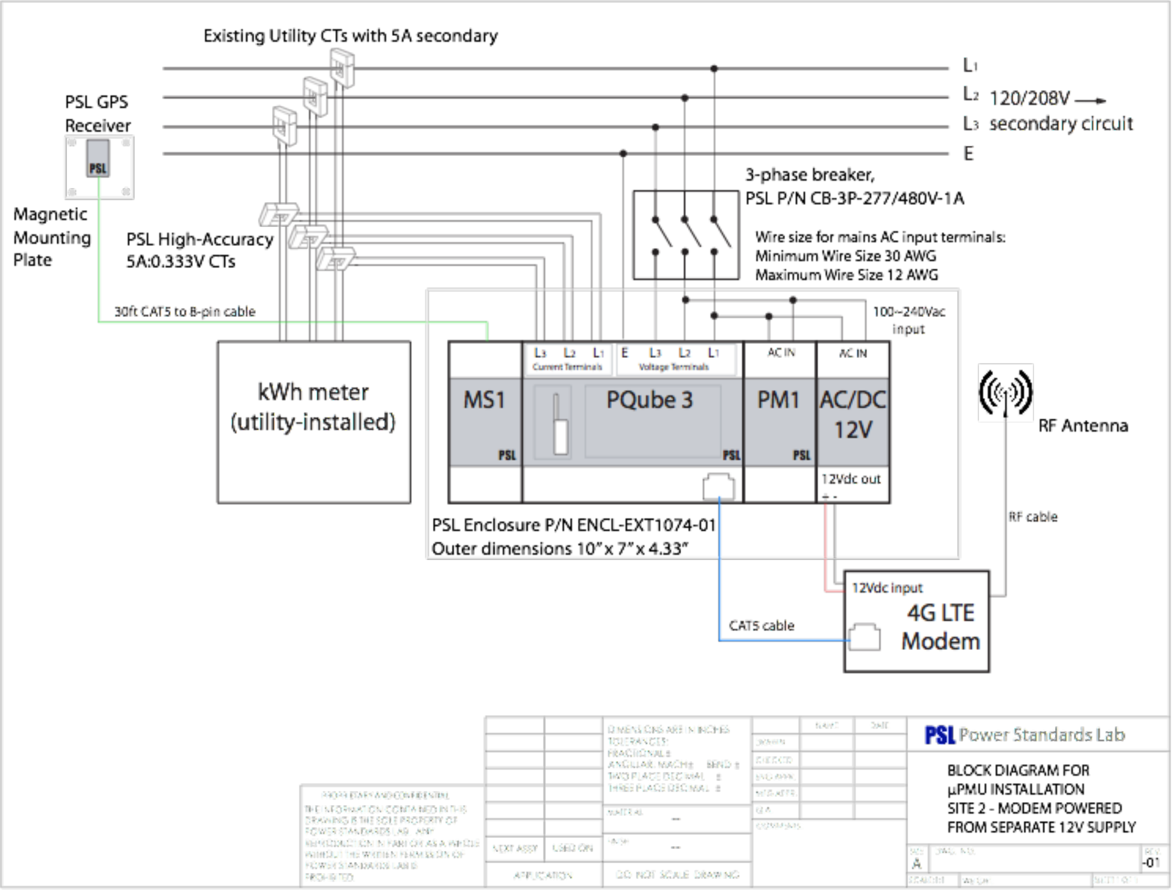

Figure 2. Block diagram for µPMU installation on 120/208V secondary circuit at a site with no convenience outlet. Courtesy Power Standards Lab (www.PowerStandards.com).

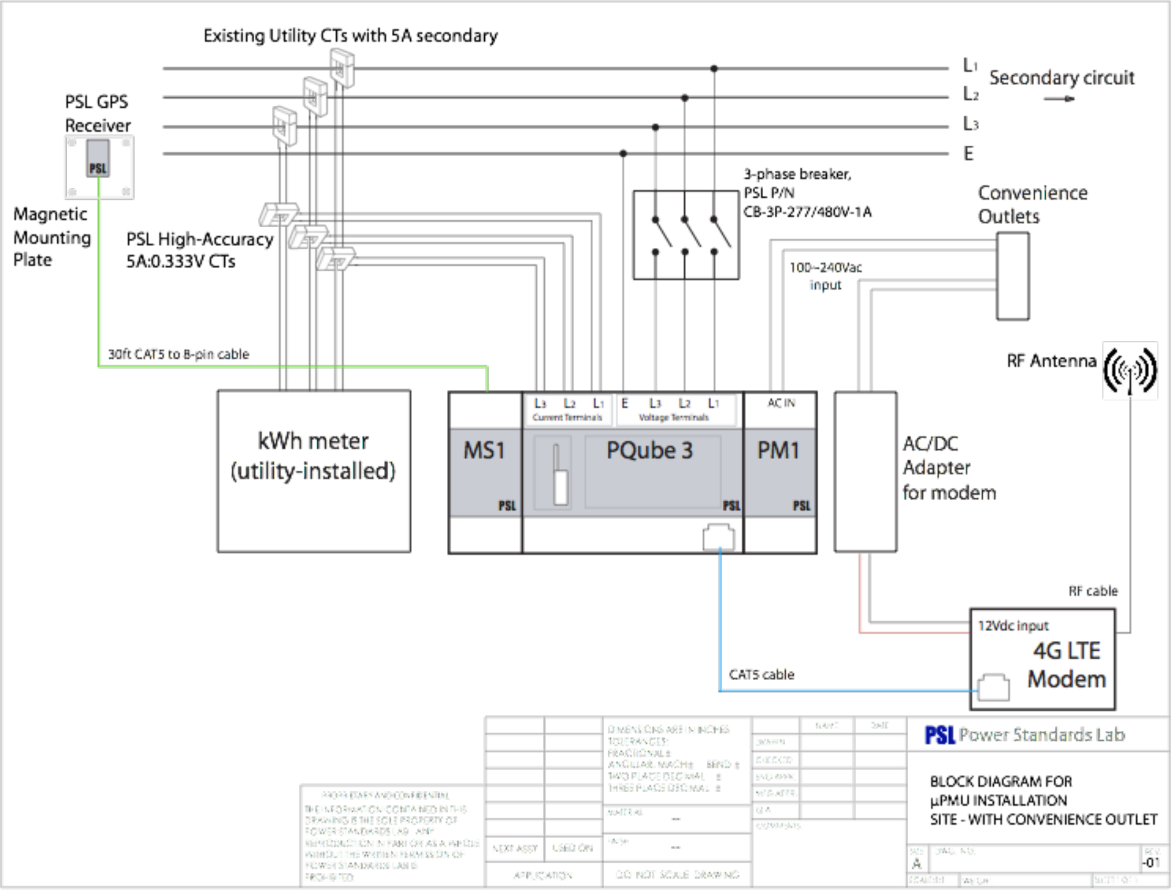

Figure 3. Block diagram for µPMU installation at a site with convenience outlets. Courtesy Power Standards Lab (www.PowerStandards.com).

Transducers

The voltage input for the µPMU may come from a single-phase or three-phase source, either
(a) directly at the secondary service voltage, up to 690V line-to-line, or
(b) from the secondary side of a potential transformer (PT).

In both cases the transformer, whether it be a designated PT or a service transformer, will degrade the quality of any measurement taken by a µPMU. Familiarity with PT accuracy classes and calibration procedures is essential to understanding the limitations this degradation will place on µPMU performance in various applications. This is discussed in more detail in the appendix of this document.

The current input, if desired, is typically taken from an ultra-high precision current transformer (CT) manufactured by PSL. Each 5A:0.333V CT wraps around either
(a) a single phase conductor of the service line to a load, or

(b) the secondary lead of an existing, utility owned CT (for purposes of metering or protection). These presently installed CTs typically are rated for a 5A output. It is not necessary to disconnect the existing CT leads to install the additional PSL CT. The error introduced by the additional CT is negligible (several orders of magnitude less) compared to the error due to existing CT's or service transformers.

The error due to existing CTs and current transformers can limit the applications in which µPMUs are appropriate, as was the case for PTs. All CTs are especially susceptible to errors in cases where the primary current is very low (less than 10% of rated values). For further discussion, please see the appendix.

A set of 3 ultra-high precision CTs manufactured by PSL, 5A:0.333V, is recommended with any µPMU that is expected to take current measurements.

Recommendations for Data Network

Each µPMU streaming on 12 channels at 120 Hz generates 124 million data points per day, on the order of a gigabyte. Data are received, compressed and stored on the Berkeley Tree Database (BTrDB). BTrDB provides online visualization through a plotter, search functionality, and the ability to access data for analysis through an API. BTrDB is open-source code downloadable from Github. In early µPMU projects, software support was provided by the researchers at UC Berkeley who developed BTrDB. As of 2017, PingThings Inc. has begun to provide software support and data hosting services.

The following options currently exist for implementing the database:
(a) Pre-installed on the Quick-Start Kit sold by PSL;
(b) BTrDB stack similar to one built at UC Berkeley; or
(c) Cloud computing services.

Option (a) advantages:

- Straightforward specifications and procurement.
- Likely the fastest, most direct path to demonstrating live µPMU data.
- Less expertise and time required from IT staff on location.
- Supported as a commercial product by PSL.

Option (a) disadvantages:

- Limited to about 2,000 uPMU-days of cumulative data per Quick-Start server. Extension beyond this capacity will require file copying/deletion procedure to archive earlier data and will not allow access to contiguous pre- and post-transition streams.
- Limited to pre-installed distillates (frequency, power, angle difference).
- Data analytics requiring other computations must be performed externally, by exporting limited batches of data (e.g. hours or days) through the API and running on Python, Matlab or Excel. This is adequate for some research purposes but supports neither production grade applications nor scalable development of innovative algorithms.

- Cannot leverage unique capabilities of BTrDB to perform extremely fast, repeated searches. This will be limiting, especially for machine learning applications.
- Cannot directly compare data between µPMUs that are connected to separate Quick-Start servers.
- Firewall is not included and must be implemented by local IT staff. It will not be possible to encrypt data using https.

Option (b) advantages:
- Scalability in number of µPMUs and project duration.
- Flexibility in design and ability to choose desired level of redundancy.
- Data store with replication reduces vulnerability to hardware failure in terms of data loss and availability (uptime).
- Flexibility in data storage, e.g. removal of unwanted streams.
- Benefit from ongoing development and improvement of BTrDB at UC Berkeley and PingThings.
- The installation can support user-defined distillates to be computed from raw data streams.
- Provides a scalable platform for ongoing and expanding research.

Option (b) disadvantages:
- High demands on local professional IT staff.
- Potentially less reliable IT support, since the server hardware would not be included in a commercial service contract with PSL.

Option (c) advantages:
- Same as (b).
- No need to worry about hardware.
- Likely highest reliability of computing infrastructure per se.
- Maximum scalability.
- Flexible payment for storage capacity based on growing data volume over project.
- Access to bursts of extremely fast computation without the need to invest in processor.
- Likely to become future standard implementation.

Option (c) disadvantages:
- Same as (b) except no exposure to hardware related risks.
- May be incompatible with up-front procurement process or administrative requirements.
- May be perceived as less secure, although there is no rigorous technical foundation for this concern.

The recommended strategy, if possible, is a dual approach: beginning with a Quick-Start Kit to familiarize researchers with BTrDB, and evolving to a scalable installation of BTrDB on a custom stack or cloud service once additional requirements have been identified.

Recommendations for Site Selection

There are a number of distribution operation issues which can be identified and addressed with µPMU measurements. Naturally, the specific install locations should be consistent with the anticipated use cases. These cases could include remedying issues such as:

- Over- or undervoltage, outside tolerance band for some customers
- Voltage sags, volatility or flicker
- Frequent outages
- Unexplained outages, e.g. breaker trips for unidentified reasons
- Phase imbalance or unknown phase connectivity
- Capacity constraints or congestion in the face of load growth
- Equipment stress or failures, e.g. load tap changers
- High losses due to heavy loading (technical losses)
- Known or suspected losses due to power theft (non-technical losses)
- Issues related to customer self-generation
- Difficulty recruiting or realizing demand-side resource potential

A number of µPMU applications are summarized in Table 1 along with their requirements for measurement quantities (e.g. voltages and currents, magnitude and phase), as well as data quality and latency, that must be considered when selecting installation sites.

Application	**Measurement Quantities**	**Time Resolution**	**Accuracy**	**Latency & Continuity**	**Phases Necessary**
Voltage magnitude profile & variability	Voltage magnitudes crucial, Voltage phase angle useful for recognition of tap changes	1 sec or better resolution is useful, synchronization between & among measurement locations critical	Changes in time of interest, absolute accuracy to 0.5% error adequate	Retain complete history	Dependent on feeder balance; suspected unbalanced lines will require all phases be measured
Awareness of real-time loads	Current magnitudes very useful, V phase angle can be proxy for current iff network impedances are known; current phase angle useful for P,Q decomposition & reverse power flow	1 cycle or better resolution reveals transient behaviors, full time domain characterization with up to 30 kHz sampling of interest to reveal harmonics	Absolute 0.5% error likely adequate	Operationally relevant latency on the order of 1 sec	Dependent on feeder balance; suspected unbalanced lines will require all phases be measured
Outage management	Voltage & current magnitudes	1 sec likely adequate	1% error likely adequate	1 sec latency likely adequate	Three phases likely necessary
System frequency & oscillation detection	Voltage phase angle essential	1 cycle or better & synchronization essential	Changes in time, not absolute accuracy of interest, 1% error adequate if stable	Retain complete history; latency requirement may vary, subsecond critical if informing protection	One phase sufficient
Island detection; Microgrid islanding & resynchronization	Voltage phase angle essential	1 cycle or better resolution	Insensitive to magnitude error, phase angle error stable to 0.01^o	Continuous monitoring, sub-second latency critical if informing protection	One phase likely sufficient unless large loading imbalance is suspected
Distribution state estimation & SE-based topology detection	Voltage phasors; sensitive to placement & number of sensors; network model & load data important	Synchronization critical	Absolute accuracy on the order of 0.0001 p.u., requires correction for transducer errors	Operationally relevant latency on the order of 1 sec	Dependent on feeder balance; suspected unbalanced lines will require all phases be measured
Topology detection based on time-series signatures	Voltage phasors	1 cycle or better & synchronization critical	Changes in time, not absolute accuracy of interest, 0.5% error adequate if stable	Retain complete history, operationally relevant latency on the order of 1 sec	One phase sufficient
Topology detection based on source impedance	Voltage & current phasors	1 cycle or better & synchronization critical	Changes in time, not absolute accuracy of interest, 0.5% error adequate if stable	Operationally relevant latency on the order of 1 sec	One phase sufficient
(ABC) Phase identification	Voltage phase angles essential	1 sec or better for time-series approach; synchronization critical	Absolute accuracy of phase angle on the order of 1^o likely adequate	No particular need for latency or continuity	All phases necessary
Model validation for line segment impedances	Voltage & current phasors	Synchronization critical	Absolute accuracy of all phasors is limiting factor, as good as 0.0001 p.u. for shorter segments	No particular need for latency or continuity	Dependent on the line's balance; recommend all phases be measured
DG Characterization; Transformer, generator & load models	Voltage & current phasors	1 cycle or better reveals dynamic behaviors; synchronization between primary & secondary side of transformer critical	Changes in time, not absolute accuracy of interest, 0.5% error adequate if stable	No particular need for latency or continuity	Dependent on load or generation balance across phases; recommend all phases be measured for high-fidelity models
Event detection & classification	Voltage & current magnitudes adequate for most events, phase angles useful	1 cycle or better, synchronization critical	Changes in time, not absolute accuracy of interest, 0.5% error adequate if stable	Continuous monitoring, operationally relevant latency on the order of 1 sec	All phases necessary if single-phase events are of interest. One phase likely sufficient to catch all major grid events.
Fault location	Voltage & current phasors	1 cycle or better, synchronization critical	Absolute accuracy of all phasors is limiting factor	Continuous monitoring, latency on the order of 1 sec	All phases necessary
Phasor-based control	Voltage phasors	1 cycle or better	Absolute accuracy critical for steady-state optimization, but stable errors acceptable for disturbance rejection	Continuous monitoring, latency critical	Highly recommend all phases be measured

Table 1. Summary of general μPMU requirements for various applications.

Considerations for choosing distribution circuits for µPMU deployment may also include the following:

- Presence of demand-side resources that can be recruited for grid services, including commercial and residential loads
- Presence of self-generating customers
- Diversity of physical layout, e.g. one long rural feeder and one urban feeder with high load density. Phasor measurements provide most recognizable insights on longer feeders with relatively high impedance
- Overhead, not underground distribution for ease of installation and modeling
- Potential for topology changes (e.g. switching tie lines in looped configuration) that can be studied and evaluated
- Existence of previously-installed PTs and CTs at points on the feeder beyond the substation
- Feasibility of installation, easy access and wiring logistics for µPMUs at locations with existing PTs and/or CTs on the circuit
- Cellular coverage at feasible install locations

Within a distribution circuit, typical µPMU installation locations include the following:

- At the feeder head/substation, to monitor the entire feeder and to serve as a voltage magnitude and angle reference for downstream locations
- Near the end of the feeder, if voltage is a concern
- Near distributed energy resources (DER) such as solar PV generators or battery storage units
- Near loads of interest
- Near possible sources of voltage volatility, or sensitive devices
- On both ends of a circuit section or line segment
- At feeder branch points

In addition to the applications of interest described above, µPMU site selection is often also constrained by a number of practical issues related to accessibility and communications. Taking these constraints into account early in the site selection process helps to streamline the installation and minimize the burden of maintenance. If possible, choose sites that:

- are accessible by the project team
- already have < 690V access through a potential transformer (PT), or the secondary side of a service transformer. This assumes that a higher-precision PT is not being installed at the time of µPMU connection. More discussion on the transformer’s effects on µPMU voltage measurements can be found in the appendix.
- provide easy access to current transformers (CTs) measuring current directly on a circuit branch of interest
- either have ethernet or good wireless signal for cellular modem
- have clear view of sky for GPS, which can be through a window; or if there is a roof, have a cable route for GPS and cellular antenna

- have enough room for miscellaneous components (power supply for modem, separate circuit breaker for µPMU, additional 5A:0.333V CTs, etc.)

A Brief Summary of the ARPA-E Project's Planning and Installation Process

The roles of the partners involved (academic researchers, utilities, PSL) were laid out in the proposal.

PSL's role was to develop the hardware and test it in their lab, using conditions that would mimic the conditions in the field. They then sent the µPMUs directly to the utilities for the first of the installations. The academic researchers did not do any additional testing prior to installation.

All the partners (utilities, researchers, and PSL) collaborated to select the installation locations and configurations and the enclosures and other hardware for the µPMUs. Sometimes an iterative process was needed (field technicians would take pictures of the area, researchers/PSL/IT support would propose an installation scheme, utilities would confirm or suggest changes).

Utility engineers or technicians performed all of the installations. While ideally a researcher would be present during the installations, in many cases, researchers were not allowed on the premises. Instead, the researchers provided a form for the utility personnel to fill out on the details of the installation. The level of involvement of the utility partners varied. Some utilities preferred to make the decisions regarding the installation and take control of the hardware. Others asked the researchers to propose the initial details of the installation (e.g. locations of components, enclosures) and then gave feedback in an iterative process.

One instance of the BTrDB database was set up to host the data. This was done by computer science researchers at UCB. Different logins were created for the online plotter tool, one for each utility that allowed them to see their own data only, and one full access login for the researchers. The utilities have wanted to see the data on the plotter and in some cases get a report from the researchers on specific events that have occurred; as of yet they have not been interested in using the API for large-scale/automated data acquisition. In newer projects, it is now possible for data to be transmitted simultaneously to BTrDB for the researchers and to the utilities via PMU standard protocol.

Two significant thermal issues were found that required particular µPMUs to be recalled. One problem was a general failure due to high temperature. In the other problem, the µPMU was installed upside down and the cooling by convection was not as effective as expected. PSL resolved both of these issues with a hardware redesign that used less temperature sensitive components. As a result, µPMUs are now hardened for installation in warm places with compromised convection. Temperature testing data is available from PSL.

Issues Deserving of Special Attention

These are a list of pitfalls and lessons learned in prior µPMU installations that should be understood prior to undertaking a new installation.

- If µPMUs may be installed in very hot environments, pay extra attention to thermal issues. Temperature testing data is available from PSL. However, if the test conditions do not fully cover the range of potential conditions and installation configurations, the user should test the devices in realistic thermal conditions and different physical configurations to minimize risk of failure in the field.
- Communication and connectivity have often been the limiting factor in the past installations, since they are often in remote locations and there is a limited amount of data storage space on the µPMU itself. As a result, it may be more valuable to have some µPMUs in easily accessible locations than to have them all in locations with interesting data but that are hard to access. The choice of modem antenna size and quality given the cellular signal strength is critical.
- Diligent recording of installation specifics is extremely important. If personnel changes happen at the utility, information can be lost unless it is recorded sufficiently. The technician performing the installation should document the process in as much detail as possible, including pictures and notes on which phases and components are connected and in what ways.
- Transducer (PT and CT) errors can be significant compared to steady-state signals of interest, even if metering-grade transducers are used. This is discussed in more depth in the appendix. Since accuracy is critical for many applications, consider whether installing dedicated PTs and CTs for the µPMU installation is worth the investment-- particularly if the existing PTs and CTs are of the less accurate protection grade.
- Recurring costs like cellular data plans and cloud hosting (if applicable) can be a significant part of the total cost of maintaining a µPMU network.
- Labor costs should also be considered, particularly if µPMUs are installed in locations that are difficult to access (e.g. in remote areas, requiring keys, or if few individuals are authorized to enter).
- The voltage inputs on the µPMU are defined as line-to-earth (line-to-ground), not line-to-neutral.
- Depending on the voltage(s) available at the installation site, the enclosure may need to have room for an extra transformer to supply the modem and µPMU.

[1] PSL, “Synchrophasors for Distribution, Microgrids: PQube 3 MicroPMU”, http://www.powersensorsltd.com/Download/MicroPMU%20%20Data%20Sheet%20Rev1_3.pdf.

Appendix: A Primer on Measurement Error Induced by Instrument Transformers

Background

When attempting to take synchrophasor measurements directly from medium voltage distribution lines, it is necessary to include instrument transformers/transducers to bring line voltages and currents down to levels that can be measured by a µPMU. These transducers are then a significant source of error in the µPMU's synchrophasor output. Transducers affect both the magnitude and phase of the µPMU's measurement, and they can drown steady-state phasor differences between measurements taken at nearby locations on a distribution circuit. This causes difficulties for a number of distribution-level µPMU applications, as has been seen in previous attempts to use µPMUs to validate the modeled impedances of short lines.

Generally speaking, we can expect any µPMU application to be affected in inverse relationship to the size of its signal of interest. This applies only to applications that depend on measuring quantities in an *absolute* sense, though. Time-series-based applications that only take into account *changes* in measured quantities will be completely unaffected by transformer error. In the former category are applications such as state estimation, voltage profile management, and load characterization in the absence of good historical data. The latter category includes applications such as phase identification, event detection, frequency measurement, and oscillation detection. For the affected category of µPMU applications, calibration and the time variance of µPMU error become a concern. This is discussed more fully in the next section.

IEEE Standard 57.13 specifies the error that a current or voltage transformer (CT or PT) is allowed to introduce into a current or voltage measurement taken from its secondary side. The standard defines a set of transformer accuracy classes, each of which has an "error parallelogram" that specifies bounds on simultaneous magnitude and angle error.

There is some difficulty involved in reading an error parallelogram because of the need for different representations of errors in magnitude and angle. Magnitude error, on the vertical axes of Figure 1, is given in terms of ratio correction factor (RCF). The RCF is a ratio of transformer turns ratios, defined for an individual transformer as the ratio between the true turns ratio of that transformer and the transformer model's nominal turns ratio. Written another way, the primary-side current or voltage of a particular transformer is equal to its secondary-side value multiplied by its model's nominal turns ratio multiplied by that transformer's individual RCF. Angle error, on the horizontal axes of Figure 1, is given in terms of transformer phase angle (generally represented as β for CTs and γ for PTs). β or γ is defined as the angle by which the transformer's secondary current or voltage leads its primary.

By way of background, the original motivation for the definition of these error parallelograms was a desire to keep watt-hour measurements taken from the secondary side of a transducer within some bounds of the true primary-side values. This real power accuracy is quantified in the transformer correction factor (TCF), which couples the RCF and phase angle through the formulas:

$$\cos(53.13+\gamma)=0.6\cdot RCF/TCF \quad \text{and} \quad \cos(53.13-\beta)=0.6\cdot RCF/TCF$$

for PTs and CTs, respectively. All accuracy class definitions are limited to a minimum power factor of 0.6 lagging, which is reflected in the above formulas.

These TCF-RCF-phase angle coupling formulas are well approximated by two simpler expressions:

$$TCF=RCF+\gamma/2600 \text{ and } TCF=RCF-\beta/2600$$

from which bounds on the TCF give rise to an error parallelogram.

A more holistic measure of error is the total vector error (TVE), which is well explained in the white paper *Synchrophasors for Distribution Systems: Technical Foundations*.[1]

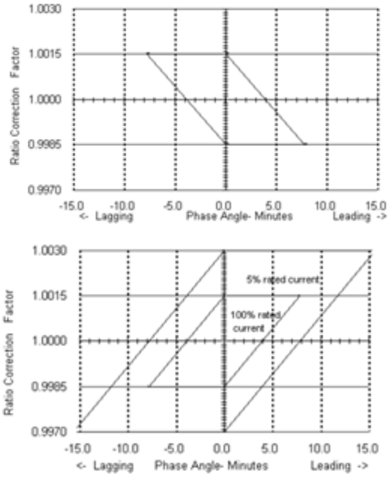

Figure A1: IEEE 57.13 Error parallelograms for Class 0.15 instrument transformers (Taken from IEEE 57.13.6)

Instrument transformer classes are named for their TCF bounds, which correspond to their maximum allowed RCF values. For a transformer of Class 0.15, with parallelogram pictured in Figure 1, the RCF must lie between 0.9985 and 1.0015. As can be seen in the figure, its phase angle error is bounded at approximately 7.5 degree-minutes. Generally, distribution-level uPMUs used in the ARPA-E project have been deployed on the secondaries of Class 0.3 CTs and PTs, with RCF values between 0.997 and 1.003 and β or γ values of approximately 15 minutes.

Deployments in which the µPMU is plugged directly into a convenience outlet are also possible. These do not require any kind of transducer, as the service transformer leading to the outlet performs all necessary step-down functions. But, these deployments are much less useful for determining medium-voltage line quantities, as they take a more indirect measurement.

Two further points concerning IEEE's specification of transducer errors are worth mentioning. The first is that the description and diagrams above apply only to metering specifications. Another class of specifications, which covers the use of transducers in relaying, defines acceptable transformer behavior during overcurrent and abnormal conditions. These relaying specifications have different nomenclature from the metering classes discussed in this section. While it is possible in theory to use relaying-class transducers with μPMUs, it is not recommended, since the errors under normal (non-overcurrent) conditions tend to be much larger.

The second point to mention concerns the difference between specifications for PTs and CTs. PTs are required to stay within the bounds of their error parallelograms only so long as their primary side voltage stays within 10% of the PT's rated value. CTs, on the other hand, are required to stay within the bounds of their error parallelograms down to primary currents of 10% rated value. Below 10% of rated primary current, the error constraints are relaxed. Between 5% and 10% of rated primary current, the allowable values of magnitude and angle error double, effectively doubling the size of the error parallelogram. Below 5% of the rated primary current, the standard recognizes that we are no longer in a portion of the transformer core's B-H curve where we can expect linear behavior. Therefore, there are no longer any limits on the error that the CT is allowed to induce once primary current drops below that level.

During normal operation of a distribution circuit, keeping voltage within 10% of a PT's rated value should not be difficult. However, CTs could certainly experience primary currents of <5%, making them a potential source of large error during low-load periods.

Calibration and the Time Variance of Error

Relative to the accuracy of a μPMU, expected transducer errors are fairly large. To realize the full benefits of μPMU precision, then, it will be necessary to remove those errors from the measurement system through calibration. Once a PT or CT has been calibrated, though, there is a finite length of time over which that calibration can be expected to stay accurate.

As can be seen in the description of RCF and phase angle in the previous section, transducer error can be modeled as a phasor multiplier (with magnitude=RCF and phase angle=β or γ) that affects measurements taken from the secondary side of the PT or CT. In most analyses, the phasor error is assumed to be a constant. This implicitly assumes that the error is systematic, likely arising from slight over- or under-winding of the primary or secondary coils, small irregularities in the iron core, and other minor physical defects.

For a more complete picture, though, our research group explored the extent to which less-predictable, non-constant factors might affect transducer error. For that effort, we examined over a year's worth of archival data for a set of two μPMUs connected to the same busbar.

Because these µPMUs are measuring an identical voltage from the secondary sides of different transformers, observing the changes in the ratio of their voltage phasors over time allowed us to draw conclusions about time changes in their error phasors.

Our measurements indicated that the PT error did see variance over time, to an extent that very sensitive µPMU applications could be expected to see measurement degradation as soon as a month after being calibrated. This speaks to the need for a low-effort means of calibrating PTs and CTs remotely, which could be used to regularly update operator understanding of their present error values. Work is underway to develop such a method, and there has been some success at the transmission level. [2] [3] If these methods can be applied at the distribution level as well, they will enable further µPMU applications and add great value to grid operations.

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[1] NASPI Distribution Task Team, “Synchrophasors for Distribution Systems: Technical Foundations,” 2018. Available: https://www.naspi.org/node/688.
[2] A. Pal, P. Chatterjee, J. S. Thorp and V. A. Centeno, "Online Calibration of Voltage Transformers Using Synchrophasor Measurements," in *IEEE Transactions on Power Delivery*, vol. 31, no. 1, pp. 370-380, Feb. 2016.
[3] ABB High Voltage Products*, Instrument Transformers Application Guide*, Ludvika, Sweden, 2015, pp. 12-13.