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Review

A Comprehensive Survey on Phasor Measurement Unit Applications in Distribution Systems

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Abstract: Synchrophasor technology opens a new window for power system observability. Phasor measurement units (PMUs) are able to provide synchronized and accurate data such as frequency, voltage and current phasors, vibration, and temperature for power systems. Thus, the utilization of PMUs has become quite important in the fast monitoring, protection, and even the control of new and complicated distribution systems. However, data quality and communication are the main concerns for synchrophasor applications. This study presents a comprehensive survey on wide-area monitoring systems (WAMSs), PMUs, data quality, and communication requirements for the main applications of PMUs in a modern and smart distribution system with a variety of energy resources and loads. In addition, the main challenges for PMU applications as well as opportunities for the future use of this intelligent device in distribution systems will be presented in this paper.

Keywords: synchrophasor technology; phasor measurement unit (PMU); communication technologies; intelligent electronic device (IED); data quality; PMU applications; wide area monitoring system (WAMS); smart grids; distribution system

1. Introduction

Worldwide, increasing pressure is being placed on the electric power grids and in particular distribution systems due to the steadily increasing introduction of renewable energy resources (RESs). For this reason, the European Commission has a long-term plan to increase the use of RESs. Based on this plan, two-thirds of energy sources in Europe should come from RESs by 2050 [1]. Nevertheless, increasing RESs cause additional uncertainties in power systems [2–7]. Increasing RES penetration with their real-time dynamic characteristics combined with the decreasing ratio of stabilizing rotational mass leads to substantial challenges for the future of power grids to keep them robust enough for the requirements and expectations of consumers. One of the important challenges of using large-scale RESs is overcapacity generation [8]. In this case, electrical energy storage (EES) is helping to eliminate the uncertainties while providing more flexibility for the system and increasing the system performance [9]. As an example [10], if PV penetration increases to 100% in the UK, 57.1% of the loads should be fed via storage systems. Moreover, the average cost of the electricity generated is defined by the levelized cost of electricity (LCOE) factor. The authors in [9] show that EES is able to reduce the LCOE factor for systems including PV and EES. In addition, EES is useful for damping controls such as oscillation damping in distribution systems. Wide-area monitoring systems (WAMSs) enable the implementation of large-scale EES in distribution systems using real-time measurement provided by phasor measurement units (PMUs) [11].

Besides RESs and ESS, active loads such as demand responsive loads and electric vehicles (EVs) will also be increasing. All of these factors introduce new challenges in the operation, planning, protection, and control of distribution grids. Therefore, distribution systems must be able to accommodate new power flow patterns in more dynamic environments. This call for new solutions is to be covered by the introduction of smart grids. In a smart grid, power generation is not centralized but rather distributed. In addition, power flow is multi-directional. However, in conventional power grids, power generation is only centralized, and power flow is in one direction. In smart grids, consumption is integrated with the system operation. However, in a traditional power grid, operation planning is top–down. Moreover, unlike conventional power grids, which are operated based on historical experience and mostly offline data, in a smart grid system, operation is according to real-time data.

Traditionally, supervisory control and data acquisition (SCADA) systems have played a great role in power systems. They are efficient and reliable operation systems. Nowadays, the challenging issues for SCADA systems have changed due to new communication technologies and the necessity of fast access to power grid information [12]. In addition, traditional power grids have limited accessibility for new devices and technologies such as flexible AC transmission systems (FACTSs), high-voltage direct currents (HVDCs), intelligent electronic devices (IEDs), and PMUs. Power utilities also face many challenges, such as reducing emission, meeting the increasing electricity demand, using RESs, using aging assets optimally, and increasing the reliability of supply and energy efficiency.

A low sampling rate (2–4 samples/cycle) and a lack of time synchronization are important problems for SCADA systems. The synchrophasor technology seems to be a good solution. PMUs are electronic devices that work based on synchrophasor technology. PMUs are more accurate and faster (up to 50/60 samples per cycle) compared to the SCADA system. In addition, they can be very useful in light of the dynamic behavior of a power system. Moreover, they can be implemented in most parts of a power system to achieve wide-area monitoring, protection, and control. However, due to the high cost of PMU installation, they are not widely used in distributions yet [13], as any new technology will add additional cost to system operators. Therefore, finding the minimum number of PMUs required and the optimal location for their installation is important for the cost-effective application of PMUs in power systems. For this reason, many studies [14–17] have been done according to graph theory to find the optimal placement of PMUs. In addition, methods have been introduced for optimal PMU placement based on their applications [18–20]. In this paper, the PMU concept as well as its evaluation and communication requirements are described in Section 2. Section 3 discusses the applications of PMU in power distribution systems. In Section 4, commercial PMU development and the capabilities thereof are presented. Finally, conclusions are drawn in Section 5.

2. PMU

IEEE 1344, IRIG-B, and IEEE C37.118 standards have described synchrophasor technology comprehensively [12,21]. A PMU is an electronic device that is able to estimate the synchrophasor, frequency, and the rate of change of frequency (ROCOF or df/dt) of the acquired voltage and/or current waveforms, according to a united Coordinated Universal Time (UTC) reference [22]. Generally, PMUs are installed into an electrical substation and interfaced to an electrical grid via standard instrument transformers. A synchrophasor is the magnitude and angle of a cosine signal of voltage/current that is measured in an absolute point in time [23]. A sine wave and its phasor form are shown in Figure 1.

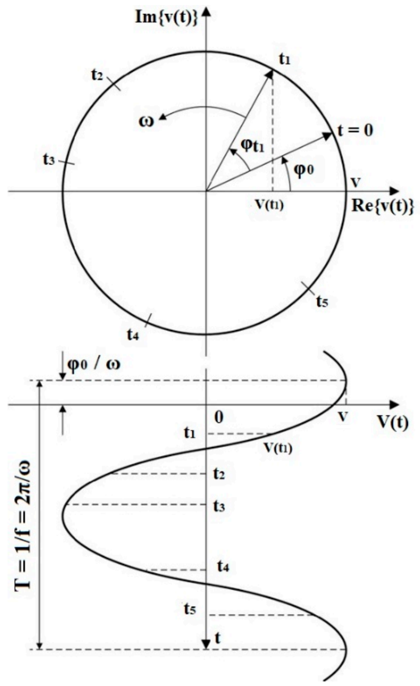

Figure 1. A sine wave vs. its phasor form [24].

The input data of a PMU are V(t) and I(t), which are measured directly from the current transformer (CT) and the potential transformer (PT). A fixed sampling rate is used with a synchronized global positioning system (GPS) clock [25], as shown in Figure 2. In power grids, similar to other commercial (non-military) uses, the civilian GPS signal is utilized. This signal has a 2.046 *MHz* bandwidth and a 1575.42 *MHz* center frequency, and it is available to all users. GPS has some advantages for power grids, such as its global coverage, free availability, and a µs level of timing accuracy [26]. However, it is vulnerable to spoofing [27]. A phase-locked oscillator is also used for time tag generating (sending out with the phasors) within the second [28]. Time tags are added to the analog voltage and current signals, which pass through a filter and an analog-to-digital converter. Then, digital data is sent to a microprocessor to compute the voltage and current phasors, frequency, ROCOF, and binary information. These data are transferred within frames [29] to phase data concentrators (PDCs), which are normally located in primary substations to be used for archiving data for any offline assessment or online monitoring of system health.

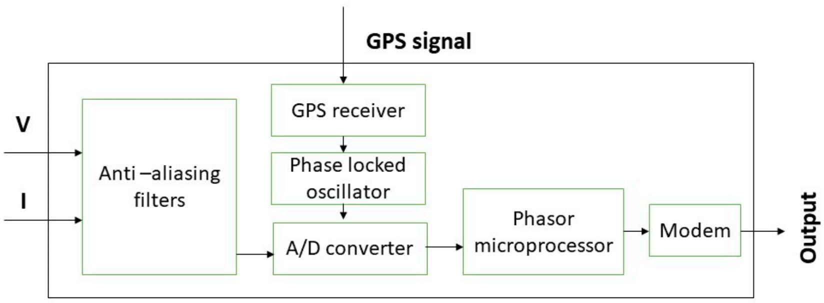

Figure 2. Phasor measurement units (PMU) block diagram.

The IEEE Std.C37.118.1-2011 [22] has determined two performance classes for PMU applications: a measurement (M) class and a protection (P) class. The M class has a lower response time but greater accuracy. It is important for applications with higher frequency requirements. The P class has a faster response time but less accuracy. It is suitable for real-time protection and control applications that require lower latency.

2.1. PMU Performance Evaluation

The main factors for PMU assessment are their availability, reliability, accuracy, latency, and message rate, which are described below:

- Availability means that data measured by the PMU can be sent to the PDC in a timely manner.
- Reliability is the strength and sufficient connectivity of the network for a prescribed performance level. A reliable and universal communication infrastructure is a crucial challenge in both the structure and the operation of WAMS communication systems.
- Accuracy is the difference between the measured value and the actual value. An accuracy index is using for the magnitude and angle, which is called the total vector error (TVE). The PMU performance standards refer to a 1% TVE [22]. However, this is changing based on PMU applications. TVE can be calculated by

$$TVE \triangleq \frac{\left|\widehat{X} - X\right|}{|X|} \tag{1}$$

$$= \frac{\left|\left(\widehat{X_r} + j\widehat{X_i}\right) - (X_r + jX_i)\right|}{\left|X_r + jX_i\right|}$$

$$= \sqrt{\frac{\left(\widehat{X_r} - X_r\right)^2 + \left(\widehat{X_i} - X_i\right)^2}{X_r^2 + X_i^2}} \tag{2}$$

where X is the true synchrophasor and $\widehat{X}$ is the synchrophasor estimated by the PMU. The subscripts r and i indicate the real and imaginary parts of the synchrophasor, respectively. In Figure 3, which represents a TVE, V is the true phasor that should be measured, V_a is the measured phasor with the magnitude error, and V_b is the measured phasor with the phase and time synch error. Amplitude errors, phase errors, and synchronization accuracy are important factors influencing the TVE value.

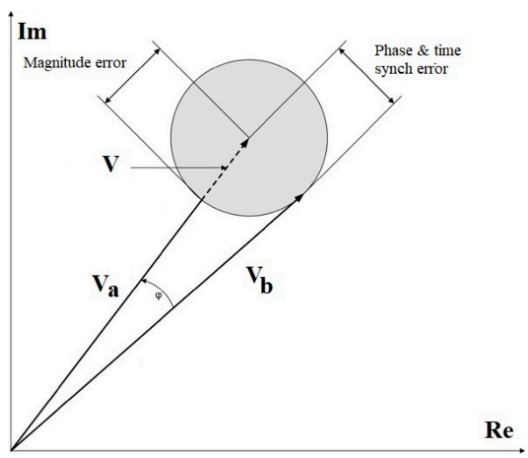

Figure 3. Total vector error (TVE) representation based on IEEE C37.118.

In the case of a zero magnitude error and a maximum of 1% TVE, the maximum permissible phase angle error is 0.573°. At 50 Hz, a full period is 360° (Figure 1), which corresponds to 1/50 of a second or 20 ms. Therefore, the time accuracy requirement or timing error is calculated as

$$Time\ accuaracy\ requirement\ (timing\ error) = \frac{0.573° \times 20ms}{360°} = 31.83\ \mu s. \quad (3)$$

Measurement error directly affects the calculations. As an example, we measure here the transmission line impedance using a PMU as a model validation technique (Section 3.3.5). Thus, two PMUs are located at two points of a transmission line in Figure 4 to measure 50 Hz sinusoidal phase-to-phase voltages. PMUs estimate voltages as $V_1 = 11.55\angle 4°\ kV$ and $V_2 = 11.25\angle 3°\ kV$ and estimate the current phasor as $I_1 = 350.0\angle 7°\ A$. Without measuring errors, the transmission line is equal to $1.02849\angle 30.05°\ \Omega$. However, by a ± 0.01° angle error, the line impedance is in a range from $1.02225\angle 29.51°\ \Omega$ to $1.03482\angle 30.05°\ \Omega$. In addition, with a ±0.05% magnitude error, line impedance is calculated with different values between $1.00101\angle 31.08°\ \Omega$ and $1.05632\angle 29.08°\ \Omega$.

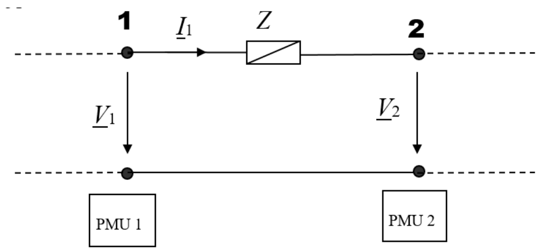

Figure 4. Transmission line.

- The latency or the time delay in a network is the time taken to transfer data from one point to another point. The WAMS latency stages are shown in Figure 5.

Figure 5. Wide-area monitoring systems (WAMS) latency stages [30].

- Message rate/resolution: A PMU takes many rapid physical measurements (samples) of voltage and/or current, computes phasor quantities from these samples, and then time-stamps and reports the phasor for each cycle or two cycles. Measured synchrophasors should be reported by a reporting rate, F_r, frequently [31]. The reporting rate is expressed in frames per second.
- Data loss: A PMU's data loss may occur due to GPS signal loss or communication network congestion. Generally, PDCs collect PMUs data based on the time stamp of the data stream. They also have a time-out function. Therefore, PMU data that does not arrive within a specified time will be dropped [32]. Based on the results of [33], most of the GPS loss events recover within a short period.

2.2. Communication

SCADA systems use power line communication (PLC), overhead lines, coaxial cables, telephone lines, fiber optics, and radio frequencies through, for example, broadcasts, microwaves, and satellites [34] to transfer data. In a WAMS, two different communication categories are used. Wired communication technologies include PLC and fiber optics, and wireless communication technologies include Wi-Fi [35], WiMAX [36], long-term evolution (LTE), cellular communication (satellite), Bluetooth, ZigBee [37], microwaves, and radio [38–42]. These methods, with their advantages and disadvantages, are described in [43,44] and are classified in Table 1. Based on this table, fiber optics has a low latency and a high reliability. However, because of the higher capital expenses (CAPEX) and operational expenses (OPEX), PLC offers a cost-effective solution, as it does not require extra wires or infrastructure. Data can be sent on existing lines that transport electrical power. Two main PLC categories are narrowband (NB-PLC) [45,46] and broadband (BB-PLC) [47]. The frequency range for NB-PLC is up to 500 *kHz*, and that of BB-PLC is from 2 to 50 *MHz*. The data rate for NB-PLC is up to 200 *kbps* and that for BB-PLC is over 1 *Mbps*. Nowadays, PLC is used for home automation, the control of city lightning, distributed energy resources (DERs), electric vehicles (EVs), automated metering infrastructure (AMI), remote metering, and demand responses. Moreover, PLC is used for the communication between substations and PMUs. Alongside its advantages, there are challenges for PLC, such as noise, attenuation, and signal distortion. Due to the low cost, infrastructure availability, and extensive coverage, PLC is still a possible option for PMU communications at medium voltage (MV) and low voltage (LV) distribution levels. In [48], a successful application of PLC for islanding in MV and LV distributions is reported. The authors in [49] introduce a new PLC technology called PLUS (Power Line data bUS). There are some advantages over the other PLC methods, such as a highly precise time synchronization solution, PLUS-TimeSync (in the range of 500 *ns*), which is provided by the communication signal, and the communication functionality, which has been developed for MTC smart grid monitoring and automation (MTC-GMA) applications. Furthermore, it has the potential to provide robust and accurate wire-fault detection and load management algorithms.

The fifth generation of mobile networks (5G) will be another, and maybe the best, option for PMU communications in the future. 5G is around 100 times faster than existing mobile technology (4G) with a transfer rate of 20 *Gbps* [50]. This new communication technology will support three important services. The first one is enhanced mobile broadband (eMBB), which provides connections with very high peak data rates and moderate rates of cell-edge users [51]. The second one is massive machine-type communications (mMTC). The mMTC will support a massive number of Internet of Things (IoT) devices with the possibility of making connections up to 10^6 per square kilometer with a less than 1% packet loss rate [52]. The idea of 5G-based IoT is presented in [53] for DER communication with a control center. The last service that is supported by 5G is ultra-reliability low-latency communications (URLLC), which are very useful for the PMU communications in distribution systems, especially in the case of protection and control, which require more accuracy and very low latency (Section 3.1). 5G-URLLC was investigated in [52] for PMU communications for state estimation (SE) in a distribution system. The possibility of using 5G for the secondary load frequency control in a maritime microgrid (MMG) was explored in [54]. Based on their study, data measured by PMUs can transmit to a control center every 0.01 *s* via a 5G network. Nonetheless, this technology has not yet been not implemented in a real power system. If this technology is to be used in the future, its security must be guaranteed.

Table 1. WAMS communication methods.

Communication Method	Advantages	Disadvantages
PLC	Available infrastructure, extensive coverage, high capacity, low cost and latency (150–350 *ms*)	High noise sources over power lines due to the noise generated by discharge across insulator, corona and switching processes, signal attenuation and distortion
Fiber Optic	High capacity, less repeaters, high security, low latency (100–150 *ms*) and low bit error less than 10^{-15}	High initial cost and high service cost prohibitive for a broad deployment in the MV or LV grid
Microwave	No cable required, medium cost	Requires a license and line of sight for operations, weather-dependent technology, signal fading and multipath propagation
Wireless (Wi-Fi, WiMAX, LTE)	Flexibility and low latency	Capacity, serious security challenges, and lower Quality of Service (QoS)
Satellite	Supports a wide geographical coverage and high accuracy	Weather conditions dependency, high initial and operational cost, high round-trip delay (250 *ms*), and high latency 1000–1400 *ms*
Radio	Working based either on licensed channels or over non-licensed frequencies	Reliability for industrial use is questionable
5G	Lowest latency less than 1 *ms* [52], highest data rate (up to 20 *Gbps*), high spectrum, network efficiency, ultra-reliability	The technology is new and it is under process; high security assurance required [55,56]

3. PMU Applications in Distribution Systems

The group of monitoring and assessment applications in power systems is called a WAMS. The SCADA system is not able to provide most of this information for power grids. As shown in Figure 6, the input data for both systems consist of an analog current and voltage, which comes directly from CT and PT. In SCADA systems, these data after processing will be sent to a remote terminal unit (RTU) as a digital RMS voltage and current. This microprocessor device interfaces devices in a real power system to a supervisory system, e.g., a distributed control system or a SCADA system, by transferring data to that system, and using messages sent from the supervisory system to control the connected devices. The communication between an RTU and a SCADA control system is based on IEC 61,850 and IEC 60870-5-104 standards.

WAMSs include PMUs, PDCs, super PDCs (regional PDCs), and communication between these parts. The output of a PMU consists of a voltage and a current in phasor form, frequency, and ROCOF. These data will be sent to a local PDC based on the IEEE C37.118.2 or IEC 61850-90-5 standards. Generally, PDCs are located at the primary substation (PS) where the collection of data from PMUs can be managed, and other PMUs within the same or neighboring PS can also communicate [57]. The important duties of a PDC include receiving data from PMUs, sending the synchronized data to super PDCs or other PDCs, monitoring the data, storing the data for event analysis, and checking for errors [58]. PDCs must make decisions with a very low latency of 10–100 *ms* (Figure 7). There are facilities for archiving data (offline and online applications). By using some IEDs, such as reclosers, switches, and capacitor banks, PDCs or super PDCs are able to protect and control the grid at the distribution or transmission level under their supervision so as to save the time and perform protection actions very quickly. Therefore, there is no need to send all the data directly to the SCADA system or the energy management system (EMS). It is sufficient to send an online alarm to the higher level; further information can be sent later on for further consideration. The authors in [59] present another idea for the future of WAMSs. In this scenario, the IEEE C37.118.2 protocol is replaced by the IEC61850-90-5 protocol for fast communication between all parts of a WAMS. Moreover, the IEC 61,850 protocol can be applied for high-speed communication between relays.

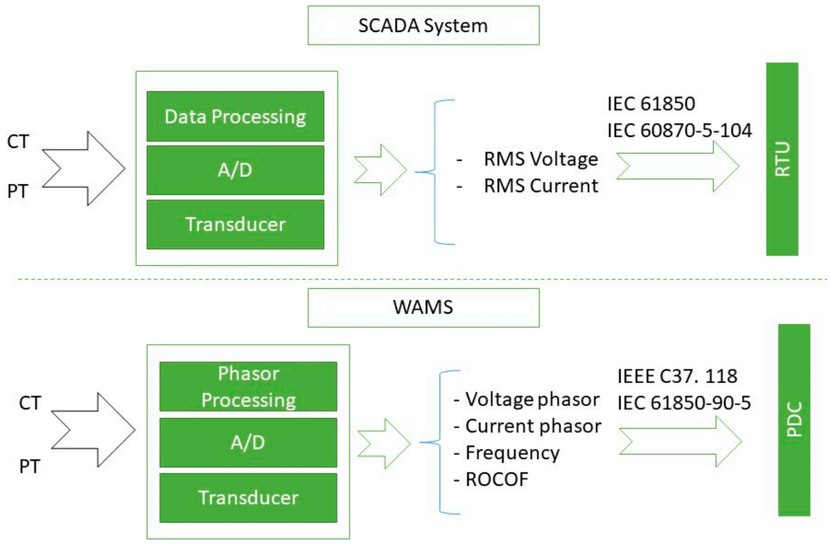

Figure 6. Supervisory control and data acquisition (SCADA) vs. WAMS.

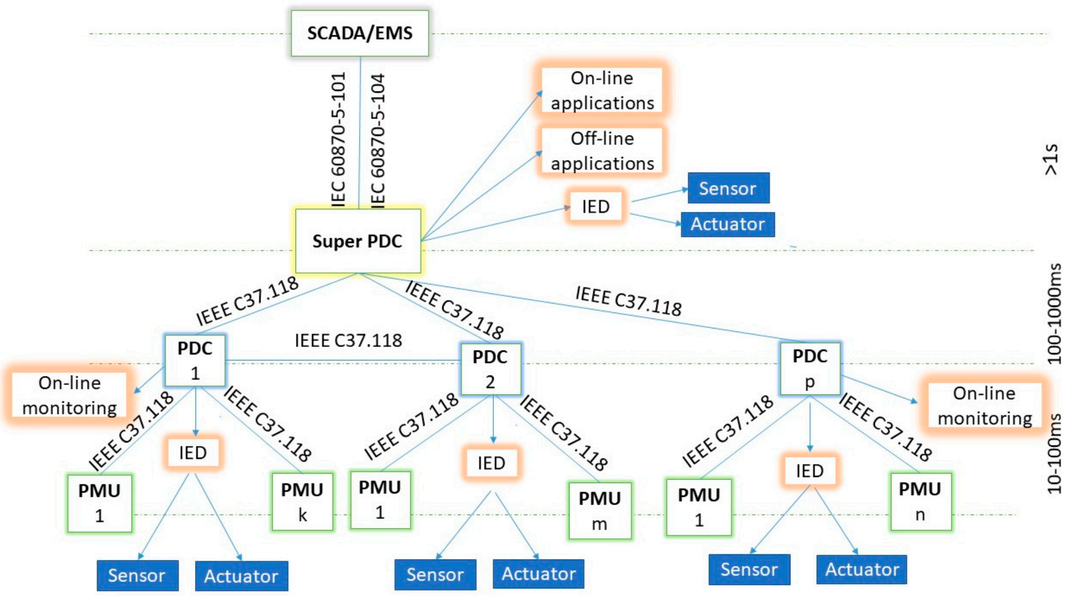

Figure 7. WAMS architecture.

In a transmission system, PMUs are utilized in order to achieve a higher accuracy of voltage magnitude and angle in order to be used in wide-area situational awareness and monitoring such as wide-area frequency monitoring, voltage stability monitoring, and oscillation monitoring and detection. Besides that, PMUs are used for SE, fault detection, and fault location. In distribution systems, because of the increasing number of active loads and RESs, PMU applications are more useful. However, the characteristics of distribution systems are less balanced, with more volatile currents and voltages. In addition, because of the small angle differences between bus voltage and line current, the transferred phasors values must be more accurate compared to the transmission system [60].

Due to the complex nature of a power system, it is very important to monitor and protect all parts of the system continuously. The main requirements to achieve the successful analysis, operation, and control of distribution networks in real time are related to the topology and state of the system. Topology is defined by the interconnection between power system components and is almost constant. However, the state (the voltage and angle for all buses) changes all the time [61]. Considering all PMU applications in the two main categories (steady state and dynamic), in steady-state applications, a medium bandwidth with continuous data transfer is required. However, the sample rate can be as low as one or two samples per cycle, with a lower data transfer. For dynamic applications, a high bandwidth and high-speed communication are necessary, even though the expected sample requirements for dynamic applications changes between 2 and 512, depending on the application [62]. Based on the North American Synchrophasor Initiative (NASPI) report in [33], PMU applications in a power system can be classified in four main classes: Automation (Class A), Reliability (Class B), Planning (Class C), and Operation (Class D), as shown in Table 2, with classifications of 4 (critical), 3 (important), 2 (somewhat important), and 1 (less important).

Table 2. Classification of PMU applications in power systems.

Class	Application	Accuracy	Availability/Reliability	Low Latency	Message Rate
A	Automation	4	4	4	4
B	Reliability	2	2	3	2
C	Planning	4	3	1	4
D	Operation	1	1	2	2

3.1. Power System Automation (Class A)

This category is related to the automated protection and control applications of PMUs in distribution systems, which are advanced applications. The aim of these applications is to improve the reliability and security, automated remedial action schemes, and asset utilization. Some of these applications with their data quality and communication requirements are listed in Table 3. In this table, the accuracy and data rates are defined based on a 50 *Hz* frequency system and can be easily changed to a 60 *Hz* system. Based on Table 3, this group of applications requires high availability and accuracy. In addition, they need a high message rate and a low latency ($\leq$ 100 *ms*) to communicate with switches, reclosers, and DER units for control reasons [63]. However, in the case of teleprotection, communication should be faster ($\leq$ 10 *ms* latency), and reliability must be very high [63].

3.1.1. Microgrid Operation

Microgrid operation refers to islanding, load and generation balance, and resynchronization. Islanding might happen after a disturbance in a power system. In this situation, the faulty part should be isolated by the main circuit breaker. Islanding occurs when the connection between the main utility and the supplying power is disconnected while the microgrid continues to supply power e.g., from photovoltaic farms into the distribution networks. There are two types of islanding. Intentional islanding is used for electric grid maintenance. Unintentional islanding occurs in fault conditions and equipment failures [64]. Active and passive methods are used for islanding detection [65]. PMUs are very helpful for islanding detection and fast distributed generator (DG) disconnection from the grid (within only 2 *s*) based on the IEEE Standard 157-2008 [66]. In this case, PMUs should send voltage magnitudes and phase angles within 50 *ms* [67]. Some research in this area has been done [68–70]. Reconnecting an islanded part of the microgrid is called resynchronization. Another PMU application in microgrid operations is resynchronization. PMUs are also helpful for balancing the power generation and load in microgrids during islanding. For any PMU applications in microgrid operation including islanding, load and generation balance, and resynchronization, voltage phase angles are essential. Microgrid operations are also insensitive to magnitude error (Table 3). In addition, a 0.01° phase angle is required [71].

Table 3. Expected data requirements for power system automation.

Application		Accuracy (μs)	Continuity	Latency (ms)	Message Rate (rep/sec)
Microgrid Operation	Islanding	<0.0174	Continuous monitoring	Sub-second latency critical if informing protection (50)	50
	Load and generation balance/frequency stability				
	Resynchronization				
Fault Detection and Location	Out of step protection	31.81	Continuous monitoring	10	50
	Low- and high-impedance faults	15.915	Continuous monitoring	20	50–100
	Equipment health diagnostics				
	Fault detection				
	Fault location	100	Continuous monitoring	1000	50
Control	Short-term stability control	31.81	-	16	50
	Phasor-based control	Accuracy is critical	Continuous monitoring	Latency is critical	50
	power system controlling with FACTS devices/smart switchable networks	31.81	-	16	50

3.1.2. Fault Detection and Location

Most faults in a power system occur at the distribution level. Traditionally, utility employees or crew travel along the feeder to find the fault location (FL) based on the operation of the protection device or the reported customer outage. Using a PMU reduces the outage duration and cost. Moreover, the accuracy of an FL can be improved by applying synchronized measurements of currents or voltages. Until now, many faults have been detected by PMUs in distribution systems [72–78]. However, some FL methods use only current or voltage phasors [79,80]. For maximum accuracy, both current and voltage phasors must be used [71]. An accurate FL requires a synchronized phasor measurement with a time resolution of at least 1/50 of a second and a corresponding time error of 100 us [47].

3.1.3. FACTS Devices

Distributed FACTS (D-FACTS) devices are commonly used for voltage profile improvement, power loss reduction, and load balancing in distribution systems [81,82]. D-FACTS devices by the injection of active and reactive power into the power grid can compensate the sensitive loads [83]. PMUs can be connected to FACTS devices or other switching protection devices to control the distribution system very quickly. For this reason, voltage and current phasors with an expected accuracy of 0.01 pu in magnitude and 0.5 degrees are needed, as shown in Table 3 [31].

3.2. Power System Reliability/Coordination (Class B)

Based on the information in Table 2 for this class of PMU applications, latency is important, and other factors (accuracy, availability, and message rate) are somewhat important as well. These types of PMU applications can be divided into topology and disturbance detection and for situational awareness. The long-term goals for these PMU applications are improving reliability, situational awareness, etc.

Situational Awareness

Traditionally, distribution systems face many challenges in achieving situational awareness because of the lower voltage and the larger number and variety of utility and customers. Moreover, the lack of high-resolution measurements (every 15 min) and accurate and up-to-date models of distribution circuits are other factors [84].

In smart grids, high-resolution voltage and current phasors measured by PMUs can be used for accurate situational awareness [85–87]. The data requirements for some situational awareness are listed in Table 4.

Table 4. Expected data requirements for power system reliability.

	Application	Accuracy(μs)	Latency (*ms*)	Message Rate (*rep/sec*)
Situational Awareness	Awareness of real-time load	15.915	1000	50
	Situational awareness dashboard	31.81	100	25
	Anomaly characterization and alarming	31.81	100	50

3.3. Power System Planning (Class C)

Power system analysis and assessment applications are in this category. Accuracy, compared to latency, is more important for these applications. The long-term goals for power system planning applications are a better system understanding and improved system modeling.

3.3.1. State Estimation (SE)

SE is used to define the present operating state of a power system. Traditionally, a set of analog measurement data, such as voltage, current, and active and reactive power, is used to estimate unknown variables. Without PMUs, all of these measurements and calculations are done by RTUs under a SCADA system, and it takes around 2–5 *s*. However, with PMUs, it is possible to observe state variables directly. Therefore, the capturing time can be reduced to 30–40 *ms* [60]. Moreover, traditional data measurement is asynchronous. Therefore, SE is a static SE (SSE) [88,89]. However, with synchrophasor technology, dynamic SE (DSE) [90–94] is used to define the steady-state voltage magnitude and phase angle at each node of the power system. An SE-based PMU is used in both the transmission and the distribution network. However, such use is more difficult in distribution systems because of the complication of distribution system modeling, and because of the phase imbalances, there is a small X/R ratio, a large number of connections, and less redundancy (from Kirchhoff's laws) [95]. SE is also sensitive to the placement and number of sensors. Moreover, the network model and load data are important for SE. SE requires an absolute accuracy of about 0.0001 *pu* [73], and requires correction for transducer errors (Table 5). The corresponding time error requirement is 0.3181 *us* [73], and the communication requirement delay is expected to be 100 *ms* [69].

3.3.2. Voltage Stability

Monitoring the dynamic behavior of voltages will help keep voltages within their limits. In addition, reactive power, peak power, and power loss will be minimized. Therefore, many studies have been done on PMU applications in terms of voltage stability and control [96–100]. Voltage stability monitoring and assessment requires a transfer time of 500 *ms* [31].

3.3.3. Power Quality Analysis

Electrical power quality, or simply power quality, means not only quality but also reliability. Power supply is without variation or distortion in frequency and waveforms (voltage and current). The most common power quality issues in distribution systems are the following:

- voltage interruption;
- voltage disturbances, such as voltage sag/swell, transient, impulse, etc;
- waveform quality problems, such as magnitude, imbalance, harmonics, flicker, etc.

A PMU helps identify changes in voltage, current, and frequency through the real-time monitoring of the system. Therefore, PMUs can be very useful for analyzing power quality issues. For power quality analysis, the expected TVE is 0.5–1% [73].

3.3.4. DG Characterization

DGs offer many advantages, including the generation of power close to the point of consumption. However, grid-connected distributed generators providing reverse power flow will cause changes to the power grid [101]:

- Increases in short circuit levels;
- Changes to voltage profiles;
- Congestions in system branches;
- Power quality and reliability issues; and
- Malfunctioning power grid protections.

DG characterization is the qualification and quantification of the behavior of grid-connected inverters to increase system stability. Online monitoring of the active and reactive power of DGs enables responses to abnormal situations. PMUs can be used for the observation of DG behavior in distribution systems. Synchrophasor technology is helpful for the following:

- Reversed power flow detection;
- Feeder voltage coordination based on DG behavior; and
- Disaggregate net metered DG from load.

For these cases, voltages and current phasors require a 0.5% TVE, which is equal to a 15.915 *us* corresponding time error in a 50 *Hz* system. There is no particular requirement for continuity or latency [102]. In addition, the expected sample rate is 50 and 60 reports per second for 50 *Hz* and 60 *Hz* systems, respectively [101].

3.3.5. Model Validation

Model validation in a power system is the validation of line segment impedances, transformers, load models, generator models, etc. A complete model should provide information regarding the impedance and connectivity of each electrical component in the power grid. Regular system model validation is necessary for a secure and reliable power system [103]. Accurate voltage and current phasors can be helpful for computing the impedances of line segments or other components. Therefore, PMUs enable a dynamic model validation. Data quality, specifically accuracy, is important for this application. For line segment impedance validation, the absolute accuracy of all phasors is a limiting factor, which should be around 0.0001 *pu* for shorter segments. The expected time error requirement is 0.3181 *us* [73]. For the model validation of other components, voltage and current phasors with an expected 0.5% TVE are required. No continuity or latency is particularly necessary (Table 5). An example of model validation is explained in Section 2.1.

Table 5. Expected data requirements for power system planning.

Application		Accuracy (μs)	Latency (ms)	Message Rate (rep/sec)
Model validation	Line segment impedances	0.3181	No particular need for latency	50/60
	Transformer and other device models	15.915		
	Load models			
	Generator models			
Power quality analysis	System oscillation detection	15.915	Sub-second latency is critical in some cases	50/60
	Transient detection and analysis		500	25/30
	Voltage stability analysis			
	Disturbance analysis/postmortem analysis	31.81	1000	50/60
	Frequency response analysis			5
DG characterization	Feeder voltage coordination based on DG behavior	15.915	No particular need for latency	50/60
	Reverse power flow detection			
	Disaggregate net metered DG from load			
State estimation (SE)		0.3181	100	5

3.4. Power System Operation (Class D)

Monitoring and visualization applications are in this class. Some of these applications with their requirements are listed in Table 6. Generally, this group of PMU applications requires a ≤ 1000 *ms* latency with medium availability. The message rate requirement for power system monitoring is very low (1–5 samples/cycle [31]).

Table 6. Expected data requirements for power system operation.

Application		Accuracy (μs)	Latency (ms)	Message Rate (rep/sec)
Topology and disturbance detection	Using time-series signatures	15.915	1000	50
	Using source impedance			
Monitoring	Real-time monitoring with reliability standards	15.915	1000	5
	Real-time monitoring			1
	Thermal monitoring (overload)			1
Outage management		31.81	1000	1 sec adequate
Phase (ABC) identification		55.56	no particular need for latency	-

3.4.1. Topology and Disturbance Detection

While voltage and frequency disturbance monitoring is very important for system stability, transient monitoring after switching helps with topology detection. Topology detection is used to define the status of switches (open/closed) in any power system location. Synchronized voltage or current phasors are useful for network topology and disturbance detection. Similar to other monitoring applications, M-class PMUs with high data accuracy and a longer calculation delay are required. Topology and disturbance can be detected based on the time-series signature or based on the source impedance [101]. In both methods, a 0.5% TVE is adequate if stable [102]. The message rate should be 50 reports per second for a 50 Hz power system, and the expected processing time requirement is 100 *ms* [102]. Some of the topology and disturbance detection methods using PMUs are explained in [104–107].

3.4.2. Phase Identification

In a distribution system, many loads are connected to different phases, and this causes current imbalances. Besides that, increasing RESs and dynamic loads such as EVs has a great impact on phase current imbalance. However, there is limited or unreliable information, which hinders the recognition of the phase of connected loads. Furthermore, phase changes are due to the frequent restoration, reconfiguration, and maintenance in the distribution system, and these problems are not always tracked continuously [108]. Incorrect phase labeling is a main source of error in diagnostic processes such as topology detection, state estimation [109], and fault location [110]. Imbalanced currents cause imbalanced voltages, which, due to a sensitivity to this result, can lead to power loss, power failure, or equipment lifespan reduction. Equipment, which is based on inverter technology, three-phase motors, and protection equipment such as relays, reclosers, and circuit breakers, is affected by voltage imbalance [73]. Therefore, correct phase identification is essential to avoid disproportionate concentrations of loads, which lead to phase imbalance. PMUs measure the voltage phase angle directly, which provides an instant visibility of phases. Therefore, a phase can be identified based on time-synchronized voltage phase angle measurements, and it is not sensitive to absolute accuracy or specific time delay (Table 6).

4. PMU Deployment

The first PMU prototype was introduced in the early 1980s by the Power System Research Laboratory at Virginia Tech. In 1991, the first commercial PMU was developed by Macrodyne, which was called 1690. Afterwards, many manufacturers started to work on synchrophasor technology. The main manufacturers and companies that develop PMUs are mentioned in Table 7. Alongside PMUs, they also develop many IEDs that work based on synchrophasor technologies. An IED is a microprocessor-based controller for power system equipment, such as circuit breakers, transformers, and capacitor banks [111]. IEDs use data from sensors and actuators for the protection and control of power equipment (Figure 7). However, a new generation of IEDs works with synchrophasor technology. Some synchrophasor-based IEDs, with their applications in distribution systems, are presented in Table 7. As can be seen in the table, they are based on the various PMU applications mentioned in Section 3. It seems that using PMUs and IEDs in distribution systems will increase in the future and will play a significant role in the monitoring, protection, and control of distribution systems and smart grids.

Table 7. Commercial synchrophasor-based intelligent electronic devices (IEDs).

Company	IED	Application
ABB	PVI-PMU (power management unit)	Photovoltaic system monitoring, active and reactive power control [111]
	RES670 2.0 (relion 670 & 650 series)	Power system protection and control [112]
	PSGuard	SCADA/EMS integration and communication, power system monitoring including power oscillation, voltage stability, and line thermal monitoring and data archiving [113]
General Electric, grid solutions	MiCOM P40 Agile	Feeder management [114]
EATON	GearGard (condition remote monitoring and early failure warning solutions)	Real-time monitoring, statistical analysis, and condition-based maintenance decisions are becoming the basis for the remote supervision of electrical equipment and systems [115]
Mehta Tec	Data fault recorder (DFR)/disturbance monitoring equipment (DME)/PMU	Online disturbance monitoring and data archiving [116]
Macrodyne	1690	Phasor measurement systems for real-time data acquisition and control [117]
	1692	Integrated recording units for transient fault and long-term disturbance events [118]
	1698, 1698E	Satellite timing units for absolute time tagging and synchronous data sampling [119,120]
Schweitzer Engineering Laboratories (SEL)	SEL-2411	Programmable automation controller [120]
	SEL-T400L	Line protection with simple configuration, accurate fault locating, and high-resolution oscillography [121]
	SEL-411L	Line current differential, distance, and directional overcurrent protection, comprehensive monitoring, advanced automation and communication, high-accuracy fault locating [122]
S&C electric company	6800 series	Control and manage distribution switches automatically [123]
Power Standards Lab (PSL)	PQube (µPMU)	Cyber-attacks detection, power consumption analysis, remotely understand commercial AC power grids, provide input for solar PV and storage control system development, simulation and data integration for solar planning tools, short-term planning and operations, to understand geomagnetic disturbance effects on distribution grids and industrial equipment [124]
Siemens	SIGUARD PDP (phasor data processor)	Complete portfolio for network monitoring, power quality recording, fault recording, phasor measurement, and system software applications [28]

5. Conclusions

Besides the advantages of using PMUs in power systems, PMU applications are faced with many challenges in distribution systems, such as inadequate phasor measurement accuracy and a lack of communication network infrastructure that can support a large number of sensors and actuators with different technologies. Therefore, using a single comprehensive data/sensor architecture is an opportunity for distribution systems to access high-accuracy voltage and current phasors using PMUs. As described in the paper, the protection and control applications of PMUs require more accurate and very fast communication technologies. It seems that by developing new communication technologies such as 5G, this problem will be solved in the near future. However, the installation of a large number of PMUs in a distribution system will be costly for distribution system operators. Fortunately, by using an efficient optimization method, the number of PMUs needed for a given system will decrease. In addition, the price of this device will likely be reduced if the use of this technology is increased and the PMU size is reduced. Thus, power systems without SCADA/EMS systems, with monitoring systems at each voltage level, and with fast protection and control action at super PDCs or even PDCs may be within reach.

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Abbreviations

AMI	Automated Metering Infrastructure
BB	Broadband
CAPEX	Capital Expenses
UTC	Coordinated Universal Time
CT	Current Transformer
DER	Distributed Energy Resources
DFR	Data Fault Recorder
DG	Distributed Generator
D-FACTS	Distributed FACTS
DME	Disturbance Monitoring Equipment
DSE	Dynamic SE
EMS	Energy Management System
eMBB	Enhanced Mobile Broadband
EVs	Electric Vehicles
FACTS	Flexible AC Transmission System
FL	Fault Location
GPS	Global Positioning System
GMA	Grid Monitoring and Automation
HVDC	High-voltage Direct Current
IoT	Internet of Things
LCOE	Levelized Cost of Electricity
IED	Intelligent Electronic Device
LFC	Load Frequency Control
LTE	Long-Term Evolution
LV	Low Voltage
MMG	Maritime Microgrid
mMTC	Machine-Type Communications
MTC	Mission- and Time-Critical
MV	Medium Voltage
NB	Narrowband
NAPSI	North American Synchrophasor Initiative
OPEX	Operational Expenses

PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
PT	Potential Transformer
PLC	Power Line Communication
PLUS	Power Line data bUS
PSL	Power Standards Lab
PS	Primary Substation
QoS	Quality of Service
OPP	Optimal PMU Placement
ROCOF	Rate of Change of Frequency
RTU	Remote Terminal Unit
RER	Renewable Energy Resources
SEL	Schweitzer Engineering Laboratories
SE	State Estimation
SSE	Static SE
SCADA	Supervisory Control and Data Acquisition
TVE	Total Vector Error
URLLC	Ultra-Reliability Low-Latency Communications
WAMS	Wide-Area Monitoring System

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