


A review of the importance of synchrophasor technology, smart grid, and applications

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Abstract. The electrical network is a man-made complex network that makes it difficult to monitor and control the power system with traditional monitoring devices. Traditional devices have some limitations in real-time synchronization monitoring which leads to unwanted behavior and causes new challenges in the operation and control of the power systems. A Phasor measurement unit (PMU) is an advanced metering device that provides an accurate real-time and synchronized measurement of the voltage and current waveforms of the buses in which the PMU devices are directly connected in the grid station. The device is connected to the busbars of the power grid in the electrical distribution and transmission systems and provides time-synchronized measurement with the help of the Global Positioning System (GPS). However, the implementation and maintenance cost of the device is not bearable for the electrical utilities. Therefore, in recent work, many optimization approaches have been developed to overcome optimal placement of PMU problems to reduce the overall cost by providing complete electrical network observability with a minimal number of PMUs. This research paper reviews the importance of PMU for the modern electrical power system, the architecture of PMU, the differences between PMU, micro-PMU, SCADA, and smart grid (SG) relation with PMU, the sinusoidal waveform, and its phasor representation, and finally a list of PMU applications. The applications of PMU are widely involved in the operation of power systems ranging from power system control and monitor, distribution grid control, load shedding control and analyses, and state estimation which shows the importance of PMU for the modern world.

Key words: phasor measurement unit (PMU); micro-PMU; Global Positioning System (GPS); optimal PMU placement; optimal PMUs placement (OPP); smart grid (SG).

1. INTRODUCTION

The electrical power system is a man-made system that is an extremely bulky and complex network. The complexities in the bulky system cause instabilities, faults, blackouts, and inconsistencies in the power supply. Therefore, it is important to identify the fault during the initial stages before it badly affects the system performance and equipment. The electrical utility mainly aims to prevent the system from large blackouts, and failures, and deliver electrical power continuously without any interruption or delay. The detection of the power network is made through monitoring systems consisting of supervisory control and data acquisition (SCADA) and modern metering device phasor measurement units [1]. Active management is needed in the power system that estimates the current state of

the distribution and transmission network using system analysis tools. State estimation (SE) plays a key role here in estimating the current state of the electrical network by removing the inaccuracies and errors using the monitoring devices such as SCADA and PMUs. SCADA system is important in the electrical network as the system is reliable and easy to operate. Although the new challenging issues consist of transfer data, new communication technologies, and fast data processing for power systems have to change the SCADA systems into new operating systems [2].

In addition, the power companies also experience too many issues while meeting the electricity demand, and consumers' requirements, eliminating unimportant data, and the use of modern devices. The issues that were found during the SCADA system operation are the low sampling rate, slow detection of errors, and inability to provide time synchronization signals [2]. The typical SCADA system from 1965 till the present counts every electrical value to ten seconds. This measurement is somehow bearable to monitor the power system in a stable condition; however, during the uncertainty and disturbance

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in the electrical network, this measurement level is not good enough to monitor the varying effects in the system. The lack of monitoring, controlling, and protecting performance in the previous devices was noticed, therefore a novel device was introduced with Global Positioning Systems (GPS) and digital signal processing (DSP) in the late 1980s in the research laboratory of the University of Virginia [3]. In the latest survey according to North America Synchrophasor Initiative (NASPI), there are nearly 2000 PMU devices installed in the North American transmission and distribution network [4]. The basic purpose for the invention of PMU is the synchrophasor measurement because it is beneficial in the distribution grids (DGs) characterization. During the operation of DGs, there is a reverse power flow in the system which badly affects the operation of the distribution power supply, failure of the DGs equipment, voltage instability, etc. [5]. Furthermore, different other important parameters are included in the operation of PMUs such as wide-area management systems (WAMS), phasor data concentrators (PDC), and GPS. A wide area management system allows the power utilities and their operators to operate the electrical effect in real-time which is done by using the new monitoring device PMUs. GPS has the advantage of timing consistency, a faster response to any event, and worldwide communication. These mentioned characteristics of GPS are useful in synchrophasor technology. Also, the lost data during communication can easily be recovered by GPS operation [6].

The application of the PMU device and wireless sensors networks (WSN) in the monitoring of the electrical grid has been observed in the last few years and considers one of the main monitoring components of power systems. A data aggression fault that is caused by the PMU has been addressed in [7] by using the wireless sensors network in the electrical grid. It is stated in the same literature that the monitored data from the PMU devices do not reach properly the server stations, therefore a sensing technology is added in the same research work to sense the values of PMU monitored data properly. The sensor device is responsible to sense all the measured data of PMU and report to the online monitoring system (OMS). Also, to further improve the accuracy and performance of the research work a binary logistic regression (BLR) algorithm has been considered.

Conventional power generation sources such as coal, diesel, gas, etc. are a cause of major climate change and are responsible for environmental pollution, which has become one of the major concerns at the current time. So the main objective is to maintain the growing energy consumption with the lowest impact on the environment and this is being done by using renewable energy resources (RES) [8].

RES has the characteristics of producing more energy at a lower cost and is environmentally friendly. RES output in generating the power is very low and fluctuating so the power electronics converter functions are used in it to stabilize and produce the power where required. The role of PMU is useful in power electronics devices such as power converters interference with RES and grid-connected inverters (GCI).

A large number of power grid data has been utilized in [9] for experimental purposes. In the same literature, an attack de-

tection model is proposed using the machine learning approach. This technique is trained using the information collected with the help of PMUs. The evaluation of the proposed model is made through the open source power systems data consisting of 37 power systems and finally, the comparison of the proposed work is made with other techniques by using a matrices evaluation process. The results show that the presented model can achieve accuracy and detection rate up to 93.91% and 93.6%, respectively. Detection case studies considering the source of the event in the power system have been presented in [10–13] by using the distribution-level microPMU. The synchronized voltage and current phasor PMU data are utilized to present the event upon the compensation theorem in the circuit theory. This circuit theory helps to generate the equivalent circuit to find any event that occurs in the power system. In [11] a capacitor bank switching event experiment is performed by a data-driven technique at a distribution grid level along a riverside. The experimental data is obtained from the PMU information to detect the switching level of the capacitor at a feeder and load level to remove the additional use of sensors for the switching purpose. In [12] the authors adopted the same approach of a data-driven experiment but on a single-phase to neutral fault on a distribution grid at a riverside. The literature also explained the study on the transition effect of faults on load and feeder levels. A data-driven experimental analysis based on lightning contingencies using the three different distribution grid levels micro-PMUs is conducted in [13], where the data is collected during a large number of lightning strikes. The focus of the research is to examine the impact and response of the 7.5 MW PV farm. Moreover, it was noticed after multiple observations that there was a reverse power flow during one of the lightning arresters which was caused by the PV side of the substation.

The real-time synchronized measurement is obtained by the improvement in monitoring, protection, and control of the power system [3]. Similarly, PMU provides the real-time synchronized measurement, synchronized frequency, rate of change of frequency of voltage, current phasor quantities, and their magnitude with a high precision rate of $\pm 1^\circ$ or $\pm 1\%$ [2–8] with the support of GPS [14, 15]. The measurement level of PMUs is very high – nearly 60 samples of measurement per cycle as compared to the traditional devices [16]. The accurate performance of PMU devices greatly affects the system estimation performance as its responsibility is to estimate the current state of the power network and improve the WAMs operation [17]. This technology increases the opportunities for the new synchrophasor devices to observe the power system more precisely and accurately. It can control the stress point, detect, and help restore early the areas which are affected in the grid. Apart from the positive side of the PMU device, it is an expensive device, and not easy for the power utilities to install at every grid station in the bulk power system. While looking at this matter, many optimization techniques have been developed to find the best places for PMU devices in the power system, and still working on it [9–11]. The optimization of a PMU placement approach is useful from the economical point of view and power system observability.

This paper presents the importance of synchrophasor technology for the modern electrical power system, where Section 2 explains the architecture of the PMU device which includes all the functional components. Section 3 discusses the phasor-represented generated waveforms and the determination between two sinusoidal signals. Section 4 explains the comparison between PMU, μ PMU, and SCADA. Section 5 consists of a smart grid definition and its relation with PMU, whereas Section 6 describes the application of PMU devices in the power system. Finally, Section 7 concludes the paper.

2. ARCHITECTURE OF PMU

The internal structure of the PMU device consists of many important electrical and electronic components that are promising in the accuracy and delivery of the PMU information. These components consist of GPS, modem, A/D converter, anti-aliasing filters, phasor microprocessor, and phase lock loop oscillator. Figure 1 depicts the complete structure of the PMU device, whereas all the installed components of the device are explained in the same section.

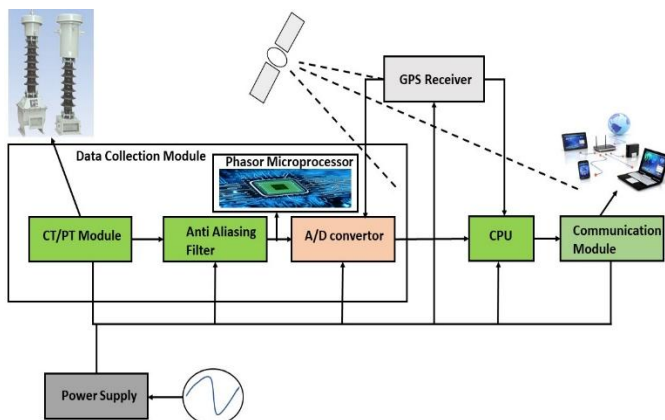


Fig. 1. PMU functional block diagram and its components

As can be seen from Fig. 1, PMU directly receives the data from the power sources such as the current transformer and potential transformer. This is the input data that is generated from the power source and then entered into the first module of a PMU device, which is an anti-aliasing filter. This analogue signal is then collected by the A/D converter to transform the analogue signal into a digital one. The digitized signal is then sent to the phasor microprocessor which calculates the synchronized data by a specified algorithm. Finally, all the internally processed data is transmitted to the processing unit and communication module for user interfacing.

2.1. PMU communication

A device that is used to interconnect PMU with other parts of a power network such as wide-area management and state estimation is named a modem. PMU generates information that is carried out and received via a modem device. The arrangement of a message is crucial in obtaining the real-time measurement

that ensures the protection and communication of the PMU information with other devices like the phasor data concentrator (PDC). Furthermore, PMU also generates different kinds of messages to interact and communicate with graphic user interface (GUI) for real-time measurement. The measurement consists of a header, command message, data, and configuration.

It can be seen in Fig. 2 how GPS [18, 19] is directly linked to PMU and its measurement devices like voltage and current transformers.

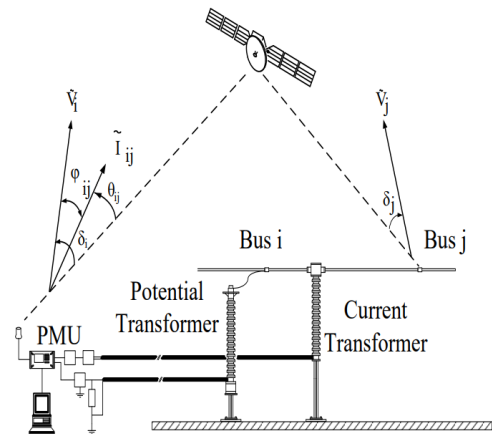


Fig. 2. PMU configuration with GPS, Current Transformer, and Potential Transformer [20]

These transformers provide the analogue data of voltage and current which is obtained from the secondary windings [21].

2.2. Anti-aliasing filter

Anti-aliasing filters are mostly in analogue forms that process the signal before the sampling. To satisfy the Nyquist-Shannon sampling theorem criteria, an anti-aliasing filter should be used before a signal is sampled to restrict the bandwidth of a signal. Once the sampling process is completed the sampling frequency of a signal should be twice as high as the maximum frequency. The data obtained from the original signal is not recoverable if the sampling rate is lower than the double maximum frequency of a signal. Therefore, anti-aliasing filters are used to limit the bandwidth of a signal to fulfill the requirement of the sampling theorem [22].

2.3. Analogue to digital converters (A/D)

Analogue to digital converters are used to get the output from anti-aliasing filters for the conversion of sampled signals. To receive an appropriate range of input signals, these signals are first received and then converted through an analogue to a digital converter. For a digitalization process, these analogue signals are transmitted from anti-aliasing filters into analog to digital (A/D) converters. After the conversion process, the phase lock loop defines the sampling rate of a signal, and then these signals are further transferred to the microprocessor via the A to D converter (ADC). Moreover, in a transmission system, six digits of ADC are used to operate the phasor quantities. These digits are divided into two parts, each half part has been assigned to voltage phases and current phases respectively [23].

2.4. Global Positioning System (GPS)

The Global Positioning System is used to accurately monitor a system response. It provides data information, facts, and the place of an object on any part of the earth's surface under different atmospheric conditions. It is based on a space navigation system; the defense Department of the USA initialized this project in 1973. It consists of 24 satellites to circulate in an orbit for operational purposes. For the sampling of input signals, these satellites are transmitting the signal of 'one pulse per second' with an accuracy of $1\mu s$. Furthermore, GPS plays a vital role in enhancing wide-area management performance and efficiently provides a path for the monitoring of PMUs measurement. GPS systems are used in road mapping, helping farmers in harvesting the fields, and especially for military applications [24].

2.5. Phase-locked oscillators

The basic concept of a phase-locked loop (PLL) is to detect the signal behavior and make a phase difference between them. This process is achieved by controlling the loop frequency and making the phase difference between two phasor signals. For sampling the data, a piece of information is coming from GPS (i.e., one pulse per second) phase lock oscillator divides this information into a suitable range of pulses per second. In a PMU device, the information is directly synchronized through a phase lock loop circuit (PLL) to get precise and accurate measurements. Afterward, the PMU device makes a high sampling rate of up to 10 kHz. Phasor differentiation between more than two phasor quantities becomes easy when utilizing the operation of the PLL circuit in PMU devices [25].

2.6. Phasor microprocessor

The sampled data by PLL and the information from GPS are received by phasor microprocessors. After that, the amplitude of voltage and current are combined optimistically. The data is processed through a recursive algorithm, which is a discrete Fourier transform (DFT). The phasor microprocessor is considered the heart of the PMU device, as it controls the flow and information of a signal throughout the system. Moreover, the two algorithms, i.e., recursive and non-recursive, which are used to compute the amplitude, magnitude, and phase angle of a signal refer to sub-parts of DFT.

2.7. Recursive method

The equation of the recursive algorithm which is used to calculate and compute the signal response is given in Equation 1:

$$x^{-N+r} = x^{-N+r-1} + \frac{\sqrt{2}}{N} (X_{N+r} - XR) e^{-jr\theta}. \quad (1)$$

For facilitation, a recursive algorithm splits the problem into smaller inputs, and after solving the problem it combines the result. Furthermore, due to more reliability, effectiveness in a calculation, and computation of the signals, a recursive algorithm is useful to compute the signal behavior. The phasor rotates in a counter-clockwise direction for the continuation of a sinusoidal waveform. To make this waveform systematically

stable, irrelevant information (error) is removed by a recursive algorithm. The recursive method is computationally intensive because the discrete Fourier transform (DFT) computation is re-generated in all phasors [26].

2.8. Non-recursive method

The non-recursive equation is used to determine and compute the matrices calculations, i.e., input/output size, which denotes the signal behavior as given in Equation 2:

$$x^{-N-1} = \frac{\sqrt{2}}{N} \sum_{K=0}^{N1} 1x_k e^{-jK\theta}. \quad (2)$$

A non-recursive algorithm has been implemented in a programming language; it is a technique for solving mathematical problems. It does not use recursion but solves all the problems without calling other approaches. It has a larger code size but is easy to implement without any time constraints. Moreover, only the recursive method has the capability of performing complex actions but sometimes both recursive and non-recursive ones can perform specific [24] tasks. It can be found that these algorithms are mostly performed in a MATLAB environment [25].

3. SINUSOIDAL WAVEFORM AND ITS PHASOR REPRESENTATION

Phasor is a key element in the electrical engineering world that represents a sinusoidal signal consisting of voltage/current magnitude and phase angle concerning a given time reference [27]. The phasor representation is defined as an angular measurement that emerges after the process of a sinusoidal waveform. To observe the power system performance, the measurement of voltage/current magnitude and phase angle needs to be identified. These known variables further help in finding the variation in complex quantities in the power system. The example of the sinusoidal signal and transferring to a phasor form is depicted in Fig. 3.

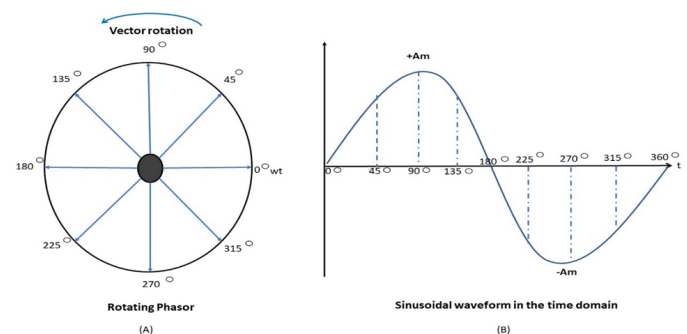


Fig. 3. Phasor representation from a sinusoidal waveform

In Figure 3, two representations of the sinusoidal signal are given. In part (b) there is a signal that has a proper fluctuating effect with the parameter of voltage magnitude and phase angle. This shows the operation of an alternating waveform (AC). Whereas, the phasor form is given in part (a) of Fig. 3, which

is converted by a PMU device without a sinusoidal wave. Another common definition of a phasor is a complex number and is represented by a pure sinusoidal waveform. The mathematical representation of pure sinusoidal and phasor is given in Equations (3) and (4) [28].

The sinusoidal equation can be written as:

$$X(t) = X_m \cos(\omega t + \theta). \quad (3)$$

The phasor representation is derived from the above sinusoidal equation:

$$X = \frac{X_m}{\sqrt{2}} (\cos \theta + j \sin \theta). \quad (4)$$

When observing the phasor form in Fig. 2 refers to part (a), it can be seen that there is no varying or fluctuating signal in the phasor form thus, zero frequency ω is recorded in the phasor representation. Phasor describes the complex number incorporated with amplitude and phase angle of the sinusoidal voltage and current waveforms. The magnitude of the sinusoidal waveform is denoted by X_m , whereas the root means square (RMS) value of the sinusoidal signal signifies the magnitude of the phasor. It is used to show the relationship between two or more two sin wave signals consisting of the same frequency.

The phasor measurement is provided by the PMU after utilizing the sampled data from the input signal. The main characteristic of a PMU is to make a phase difference between two or more than two signals to clearly understand the difference between two sinusoidal signals, and its phasor form is presented in Fig. 4.

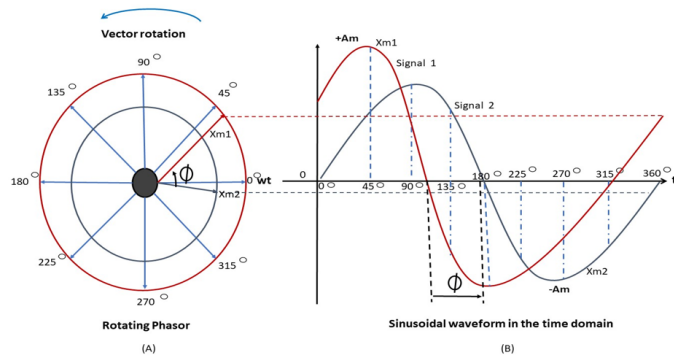


Fig. 4. Sinusoidal and phasor differences between signal 1 and signal 2

When observing the phasor form in Fig. 2 refers to part (a), it can be seen that there is no varying or fluctuating signal in the phasor form, thus, zero frequency ω is recorded in the phasor representation. Phasor describes the complex number incorporated with amplitude and phase angle of the sinusoidal voltage and current waveforms. The magnitude of the sinusoidal waveform is denoted by X_m , whereas the root means square (RMS) value of the sinusoidal signal signifies the magnitude of the phasor. It is used to show the relationship between two or more two sin wave signals consisting of the same frequency.

The differences between the amplitude of signal 1 and signal 2 can be seen in Fig. 4. Synchro-phasor measurement is

the measurement of voltage/current amplitude and phase angle obtained in real-time synchronized measurement. The complex number of the sinusoidal signal of voltage/current magnitude and phase angle denotes a phasor at a given time domain. Furthermore, the amplitude of the sinusoidal waveform refers to the magnitude of the signal whereas the determination of the phase angle is described by the time reference as shown in Fig. 4. For sampling purposes, the sampled data from the given time reference is used to estimate the phasor behavior [29].

4. COMPARISON BETWEEN PMU, μ PMU, AND SCADA

The performance of the SCADA system relies on a steady-state power flow analysis, while the operation of the PMU and μ PMU is based on the real-time synchronized measurement of voltage and current phasors with high accuracy and faster sampling rate. The μ PMU was initialized in the distribution and transmission network before the introduction of PMU. PMU provides synchronized, accurate and precise data which is achieved with the help of GPS [30]. The consideration of PMU was needed to cover the wider area of the transmission network due to the limited operation and monitoring capabilities of the μ PMU in the distribution and transmission network. The μ PMU has a sampling rate of 10–120 samples per second which can be adjustable for the system having a 60 Hz frequency. Table 1 shows a small number of characteristics of SCADA and PMU technology.

Table 1

A comparison of a few features between SCADA and PMU

S. No.	Features	
	Conventional grid and SCADA	PMUS
1	Limited in operation	Extensive in operation
2	Mostly manual operating system	Manual, automatic, and decentralized operating system
3	Limited to users and companies	Expanded electricity market for consumers, users, and companies
4	The slow response rate in an emergency condition	The response rate is high
5	Slower reaction time than the modern grid	Faster and quick reaction time

The model of the μ PMU with the name PQube3 used in Power Standard Lab (PSL) and an arbiter PMU are shown in Figs. 5 and 6 [31].

Some features of μ PMU, model PQube3 are listed below:

- It provides synchronization measurement using GPS.
- Capturing the data at the rate of 120 cycles per second at 60 Hz.
- The data include the measurement of voltage and current phasors, real and reactive power, and power factor.



Fig. 5. PS laboratory used μ PMU with the name PQube3 [32]



Fig. 6. The Arbiter PMU with the model number 1133A [32]

- The rated nominal voltage is 100V AC to 960V AC, which can be measured as a line-to-line connection, and 69V AC to 480V AC, which can be measured in line to neutral connection.

Some of the commonly used PMU models with their manufacturers are listed in Table 2.

Table 2

Commonly used PMU models and manufacturer companies [20]

S. No.	Manufacturer companies	
	Manufacturer	PMU model number
1	Siemens	Extensive in operation
2	Utility System, Magnetic Instrumentation Company	Simeas R-PMU
3	Schweitzer Engineering Laboratories (SEL)	PMU20002
4	Macrodyne, inc.	SEL-421
5	ERL	Model 1690
6	Arbiter Systems	Tesla 4000
7	Alstom	Model 1133A
8	ABB	P847B&C
9	Imagination at work	RES 521

From the above table, the PMU manufacturer name Arbiter Systems with the PMU model 1133A is used for the monitoring purpose and its characteristics are given in Fig. 3:

- GPS helps in synchronized measurement.

- The measurement rate of the phasor quantities is 60 cycles per second at a 60 Hz frequency.
- The range of the input voltages is 0–69, 120, 240, and 480.
- The input frequency ranges from 4%–65% Hz.

5. SMART GRID AND ITS RELATION WITH PMU

A smart grid (SG) is a widely distributed electrical network as it incorporates data information and communication to ensure real-time measurement between the utility and its consumers. According to the European Union and Electric Power Research Institute (EPRI) definition of the SG, it incorporates the actions between the power utilities and its consumers ranging from generation to consumption. This ensures reliability, and efficiency, economically, reduces overall cost and enhances market and power service, and security of both sides. It uses smart meters, sensors, communication and protection devices, and computers for the proper use of secure, reliable, and efficient power systems [33, 34].

The most important feature of the smart grid is to measure the voltage and current phasor and make a difference between them if the differences are lower or higher than the set limit. This results in the unwanted tripping of the protection devices (relays) and blackouts [35, 36]. In such circumstances, the PMU device is highly recommended for a better understanding of the grid condition when there is a risk of protection, malfunction, and shortage of the power supply [37]. A study conducted in the year 2012 about worldwide energy consumption reveals that it is likely to increase by 48% and the net generation will be expected to increase by 69% energy demand. Also, the increase in unconventional energy sources has been noted as compared to fossil fuels [38]. In reference [36], the power system is responsible for 25% of worldwide greenhouse gas emissions. The utilization of renewable energy and distributed generation will certainly eliminate the risk of greenhouse gas emissions. Therefore, SG needs proper monitoring, control, and communication between interconnected networks.

The integration of renewable energies such as solar PV plays a vital role in the implementation of a smart grid. A comprehensive review of the solar photovoltaic module is presented in [39]. The research work considers the compound parabolic concentrators (CPCs) design and applications for PV systems. CPCs can collect both direct and diffuse solar radiations and are suitable for smart grid installation.

5.1. Characteristics and function of a smart grid

SG uses smart systems consisting of smart meters, communication, monitoring, and service control devices. Some of the SG characteristics and functions are:

- It provides various conceptual model domains in utility, consumers, generation, transmission, distribution, market, and operation.
- It allows consumers to minimize the use of power on their choice this prevents the extra use of power and saves energy, and additional cost, optimizing the function of the power system.

- It provides two ways of communication by exchanging data between consumers and utilities.
- It consists of many small residential and distributed grid generators, which facilitate the nonstop use of electricity.
- It uses smart metering systems such as advanced metering infrastructure (AMI) to measure the data in real time and inform the user about using the electricity at an hourly price rate.
- It assists in the real-time determination of electrical equipment such as transformers, generators, transmission, distribution lines, etc.
- It improves the power supply by predicting and reacting in no time; this enhances the reliability, security, and efficiency of the system.
- It ensures the continuity of the power supply all the time, even during cyber and physical attacks, damage, and in any disastrous event.

It helps in educating the customers about how to effectively use electricity in their houses, offices, industries, etc.

A complete overview and operation of the smart grid are shown in Fig. 7.

A smart grid is a new way of using advanced technologies and generating information to communicate between consumers and power utilities. This will bring revolution in the traditional approaches to power systems [40]. The contribution of SG to the use of renewable energy is to reduce man-made dan-

gerous greenhouse gases, which also helps in the reduction of wasted energy [41]. Also, SG deployment into power systems can ensure that it does not contribute to climate change and greenhouse gas emissions.

6. APPLICATION OF PHASOR MEASUREMENT UNIT IN A SMART GRID IMPLEMENTATION

Different research groups and engineers are working hard on the installation of a new technological device in several utilities around the world. Due to its speedy analysis of measurement, synchronization of data becomes possible, which is beneficial to facilitate future generation with improved electrical supply without any flicking of electricity. Instabilities in the variations of voltage and phase angle can be observed, which helps in predicting future events, likewise, the operator can easily predict the disturbances in a system with the help of PMU measurement. Furthermore, the basic requirement in the execution of the smart grid is obtaining highly precise synchronized data, which is now possible by PMU. It also helps in the improvement of system state estimation performance. Some of the common applications of PMU from the initial stage till now are explained in the following sections.

6.1. Premature application

During the initial stages of PMU, it was first used as an application of post-mortem event analysis as a system disturbance

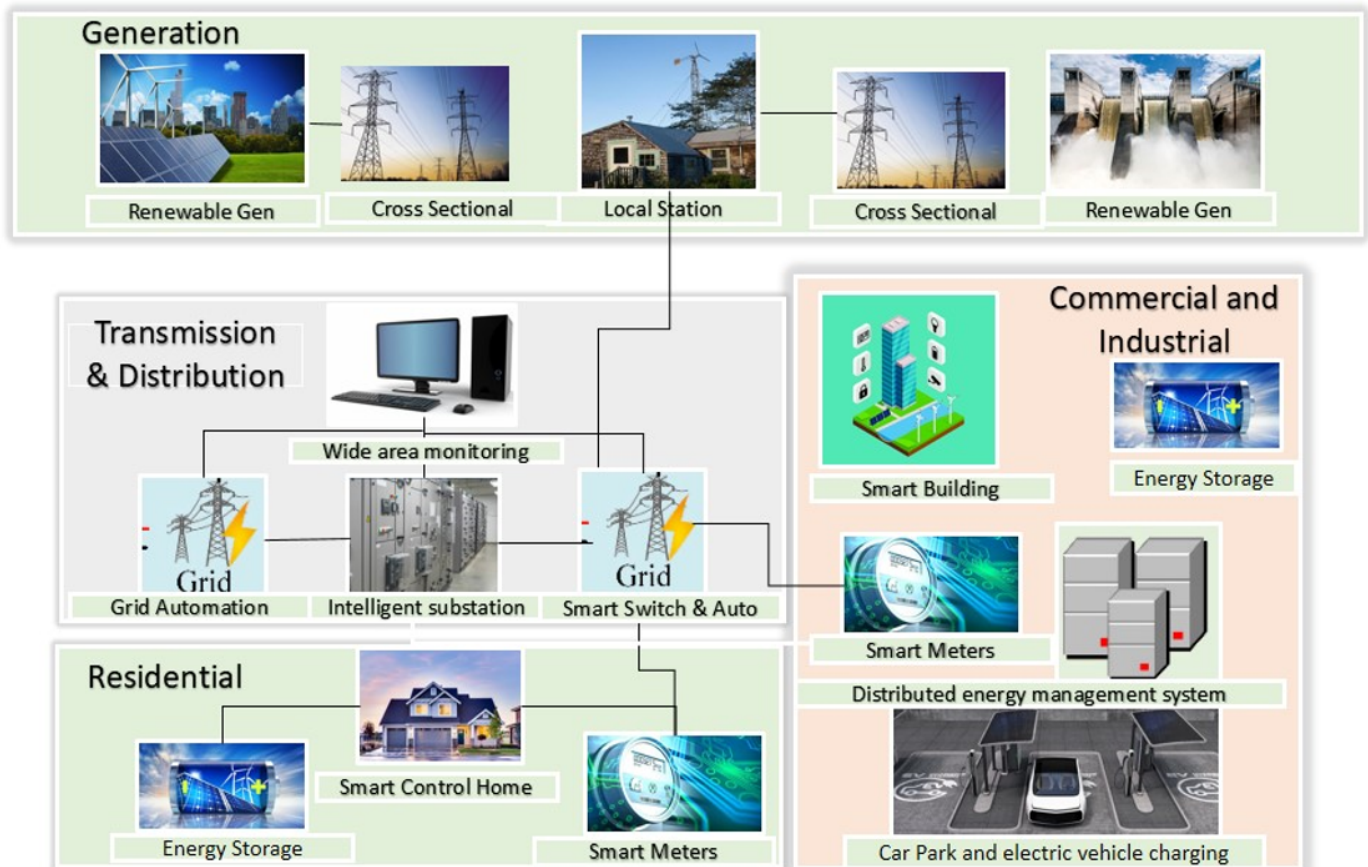


Fig. 7. Concept of the smart grid working principle

recorder (SDR). Due to lacking device availability and other practical limitations of bandwidth restricted its installation towards the modern smart grid concept. Only the positive sequence voltage/current phasor was provided by the PMUs at that time because of the bandwidth restriction [42]. The initial installation stage of PMUs was successful in the post-event investigation, which further led to the installation of several more locations in the United States and Europe. With the help of DSDR, PMU devices were able to gather productive information that assisted in the applications of a monitoring device.

6.2. Power system protection using PMU

Power system always faces severe instabilities in their measurement, and any uncertainty in measurement devices causes failures in the system. To protect the power system from losses, a PMU modern device is developed to overcome the shortcomings which could be harmful to generation, transmission, and distribution circuits. The protection scheme is one of the main elements of any system that secures and isolates the operational components that are found under faulty conditions. The protection scheme changes according to the change in the state variable condition. An adaptive relaying concept is usually originated from PMU infrastructure to overcome the variation in faulty conditions. It quickly isolates the system from the faulty side and prevents it from power outages and blackouts. PMU is useful in detecting the instabilities in the power supply, therefore, an operator can easily make a productive decision when they find any uncertainty in the electrical measurement [43].

6.3. State estimation using PMU

State estimation is used to estimate the real-time monitoring of power networks under different circumstances. It gives the estimation of power variables and then checks the consistency of these variables for the continuation of measurement. It is an integral part of energy management systems and detects the condition of an error, identifying and eliminating it, based on the modern feature of the PMU device. It uses different calculation processes such as iterative, mathematical modeling, and computation programming to calculate the state of variables. These measurements consist of voltage, current, phase angle, and active and reactive power which are received from the various substations. Before the deployment of PMU, the conventional state estimation used the measurement of active and reactive power to observe the voltage magnitude and phase angle in the power system. Modern technology has transformed “state estimation” into “state measurement”. During the operating system state estimation faced some problems which are described below:

- Input data becomes noisy due to the existence of an error.
- It is difficult to find and separate the errors from the information.
- It is difficult to observe the system.
- A huge calculation time is needed to solve the issue.

6.4. Power system control using PMU

Flexible alternating current transmission system (FACT) devices with the collaboration of PMU provide compensation for

reactive power and improve the capability of the transmission system. These devices are used for the feedback of signals in a power network. The main objective of the FACT device is to control the power system operation and accurately utilize the available data of the transmission network. It is used to solve the issues of unrestrained flows of the loop and control the power flow as well as improve the heavily loaded area. Mathematical modeling of calculation is used to operate the controlling action, but these modelings do not provide accuracy under dominant conditions, which may result in the imperfection of controlling function operation. Hence, the synchronized data which is attained by PMU makes it possible for system limitations to direct feedback from the remote areas to the controller. Therefore, the combination of the PMU controller and the local controller will increase the complete strength of the electrical network [44].

6.5. PMU measurement is used in load shedding control

The utmost important application of PMU is in the use of a flexible load-shedding scheme [45]. In a practical scenario, PMU is generally used to maintain the original condition of a network such as the consistency and controllability of a system during the power supply to the consumer end. Load shedding is an alternative control structure in a network that is used to operate the electrical network under normal working conditions. The current method of load shedding relies on the frequency and rate of change of frequency (ROCOF) which gives a better concept and analysis of the load shedding scheme to enhance validity. The advancement in monitoring PMU devices improves all the states of the power system. Likewise, the reduction of disturbance from the system can be achieved using synchronized PMU measurement of voltage magnitude, signal frequency, and phase angle.

6.6. PMU detections

When excessive current flows through the electrical circuit or any outside object interrupt the continuity of power flow, it may result in the occurrence of a fault and further disturbs the performance of the power system. The fault causes instabilities in the measurement, which can lead to an outage of a transmission line. Different protecting techniques are used with PMU devices to find the exact faulty location to restore the electricity service under normal operating conditions to the consumer side. In [46], a mathematical technique is presented based on the synchronized measurement of PMU. PMU is installed at both ends of a transmission line and provides synchro phasor signals to the wide area management system which helps in estimating the location of a fault.

Moreover, an identifying fault technique is proposed in [47], in which during the existence of any fault two components are used in the presented work to resist the intensity of voltage and the direction of power flow. To pinpoint the disturbed location, it determines the direction of fault current by using phase angle and the measurement of positive sequence magnitude of voltages at preferable buses. References [48, 49] presented a new algorithm in which it is recommended that the use of PMU helps to solve the OPP problem and spot disturbances in the

measurement. These techniques are based on the accuracy of PMUs and are involved in two stages. First is the pre-location step and the second is the correction step which is mainly used to estimate the interrupted area and voltage drop. A new fault diagnosis and location technique have been presented in reference [49] for the active power distribution grid. This technique includes the synchronized PMU data using the matrix information to identify the location of the fault and determine the fault type.

6.7. PMU monitors the distribution network

Currently, a steady change in the distribution network from passive to active power system includes the main deviation in their functional process. The changing process has been done by using new smart metering PMU technology and it gives stability and accuracy during the observation of a power network. As the SCADA system finds difficulties in monitoring the distribution network performance and cannot provide the desired output of real-time state variables. Thus, the application of PMU is applied in the monitoring of distribution networks due to the limitations of traditional approaches. In [50], a Micro- μ PMU is used to provide real-time monitoring to a distribution network. The novelty of this literature is to isolate the heavily loaded area into an equivalent data stream. Afterward, the data stream of the parallel combination provides the effective measurement of real-time state estimation. The concept of μ PMU is useful in controlling and protecting the distribution station by providing reliability in the power load.

A complete overview of the techniques of data analytics and islanding detection of distribution systems using phasor measurement unit data is presented in [51]. Other limitations related to islanding events have also been discussed in the same research work

Correspondingly, M. Paolone *et al.* presented a new model of PMU [52], for a specified dynamic distribution system. In this work, a vast number of techniques are precisely used to estimate the state variables. Similarly, its applications exist in real-time monitoring for both stable and unstable states. In [53], the problem with the assessment of the distribution system and the execution of the smart grid is discussed. It is stated in the given literature that some common circuits help in increasing the nature of total harmonic distortion (THD) on distribution generation feeders which may result in a decreasing power factor. To get the improved power factor THD must be kept low according to the circuit requirements. Therefore, the installation of PMUs at desired places in the distribution network is essential in the process of getting synchronized measurement and this can improve the performance of distribution equipment. The varying negative effect of distributed generation can be reduced with the advancement of a monitoring device.

Over the past few decades, massive progress and development have been made in the electrical power systems from generation to consumer and the monitoring of the power system is important in this regard. Therefore, numerous PMU devices have been installed across the globe. A survey was conducted in 2017 about the installed number of PMUs, which is shown in Table 3.

Table 3

Installed no. of PMUs in their respective countries [20, 54]

S. No.	Countries with installed PMU devices	
	Countries	No. of installed PMUs
1	North America & China	1000
2	Mexico	272
3	India	130
4	Brazil	1000
5	Finland	20
6	Italy	20
7	Spain	13
8	Australia	12
9	New Zealand	10

7. CONCLUSIONS

The focus of this paper is to deliver the significance of the phasor measurement unit for power systems. The conventional power network is transitioning to a smart grid which needs smart devices. PMU is one of the main elements that is needed for a smart grid. Therefore, in this paper, the importance of PMU synchrophasor technology and its applications that mainly focus on the minimization of installation cost and energy consumption has been presented. The adequate response of accurate, fast, and reliable measurement of phasor quantities explains how important is the need for PMU for the power network. The sinusoidal waveform, its phasor representation, and the difference between the two signals are also discussed in this paper. Since PMU is a modern device and has many capabilities of monitoring, controlling, and protecting the power system much better than previous devices, its operation and usage in different areas are widely considered. Moreover, its application involves power system protection and monitoring, load-shedding control, and distribution network coverage which differentiate its characteristics from other devices. Furthermore, a small comparison between PMU, microPMU, SCADA, and a definition of smart grid and its relation with PMU has also been discussed in detail. The information in the paper can be extended for future work when considering the applications of a PMU device. For the manufacturing side, the architecture components of the PMU device can be minimized to reduce the extra functioning burden, which reduces the cost of some important components to work more efficiently. The application can be extended to micro-distribution grid implementation, and improve conventional distribution grid performance.

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