Chapter 57
Applications of Synchrophasors Technology in Smart Grid

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Abstract Synchrophasor technology is now widely accepted throughout the world. The driving force is the increasing complexity of the modern power system, which has caused numerous power outages around the world. It enables efficient resolution to substantially improve transmission system planning maintenance, operation, and energy trading. Their efficiency is examined on diverse applications all around the globe in the area of transmission and distribution system. This paper explains various applications offered by synchrophasors technology in the modern power system.

Keywords Phasor measurement unit (PMU) · Wide area measurement system (WAMS) · Phasor data concentrator (PDC) · Wide area control (WAC)

57.1 Introduction

The nature of the large interconnected modern power system is becoming complex day by day due to the introduction of large dynamic loads, integration of renewable energy resources like solar, wind, etc. [1]. Several severe blackouts have been occurred throughout the world the driving force of which remain unnoticed to the power system operators to prevent their occurrences. These outages necessitates the precise monitoring of critical grid parameters such as frequency deviation, power flows, voltage, angle, etc. Therefore, it is necessary for the utility to develop such a system that can monitor, control, and protect its element from generation to distribution [2, 3].

In the past few years, the power system mainly depends on traditional supervisory control and data acquisition system (SCADA) for processes and control. These

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Table 57.1 Comparison between PMU and SCADA

Parameters	SCADA	PMU
Measurement	Analog	Digital
Resolution	2–4 samples per cycle	Upto 60 samples per cycle
observability	Steady state	Transient
Monitoring	Local	Wide area
Phase angle	NO	Yes

measurements are not time-stamped and are unable to capture the completed dynamic of the grid. They have very slow data scanning rate of about once in 4 s. This can lead to insufficient capturing of actual dynamics of the system due to slow scanning rate, unsynchronized measurements, etc. [4].

Toward this direction of achieving the total grid observability, synchrophasors technology is widely accepted across the world. This technology involves installation of PMU across the grid that has very high sampling rate of about 25–60 samples per second and makes it a highly suitable device to capture the accurate dynamics of the system. Another advantage of PMU is its ability to provide synchronized measurements that enables the grid operator to analyze the stability of the large interconnected system effectively. They have proved its potential worldwide in enhancing the situational awareness of the grid operator to ensure safe and reliable grid operation. A summary of performance comparison of SCADA- and PMU-based system is given in Table 57.1 [5, 6].

This paper discusses various applications that the synchrophasor-based wide area monitoring system offer to modern power system that includes real-time monitoring and control, modal analysis, dynamic state estimation, contingency analysis, system planning, etc. The rest of the paper is divided in to the following sections. Section 57.2 provides the basic concept of synchrophasors technology. Section 57.3 gives an overview of synchrophasor-based wide area monitoring system. Section 57.4 discusses potential synchrophasors applications in smart grid. Section 57.5 presents a case study of an application of synchrophasors in Indian power grid under fog condition. The conclusion is drawn in Sect. 57.6.

57.2 Synchrophasors Technology

The phasor synchrophasor considers the sinusoidal signal represented as a pure sinusoidal waveform [6–8].
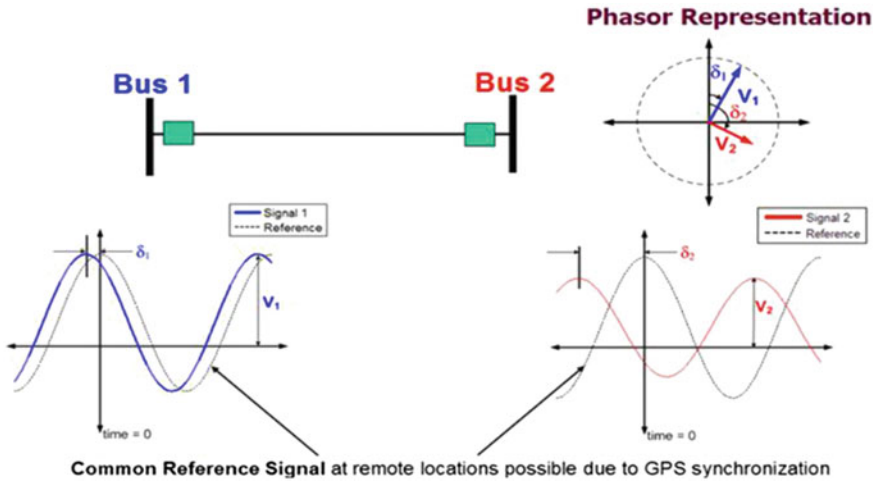
$$X(t) = X_m \cos(\omega t + \varphi) \tag{57.1}$$

Fig. 57.1 Common reference for the phasor calculations at different locations

where X is the amplitude signal, ω is the frequency in rad/s, ϕ is the phase angle in radian. The rms value of X is.

The phasor of sinusoidal signal is given by $X = \frac{X_m}{\sqrt{2}}$.

$$X = X_r + jX_i = \frac{X_m}{\sqrt{2}}e^{j\varphi} = \frac{X_m}{\sqrt{2}}(\cos\varphi + j\sin\varphi) \tag{57.2}$$

From Eqs. 57.1 and 57.2, the sinusoidal signal and its phasor representation are shown in Fig. 57.1. The positive angles are estimated in an opposite clockwise direction from the actual center. Even if the frequency of a sine wave was applied in the phasor determination, the phase variation is (0); hence, the phasor becomes $= \frac{X_m}{\sqrt{2}}$.

57.3 Synchrophasors-Based Wide Area Monitoring System

PMU-based wide area measurement system plays an important role in safe and reliable gird operation. Whenever fault appears in the system, the wide area security system uses the online measurement data to discover the faulty buses and, consequently, the faulted line to isolate it from rest of the system. They are playing a significant role in modern studies related to energy system transient stability [9, 10].

A simplified architecture of PMU-based wide area monitoring system is shown in Fig. 57.2. Its key components are [1, 11–13].
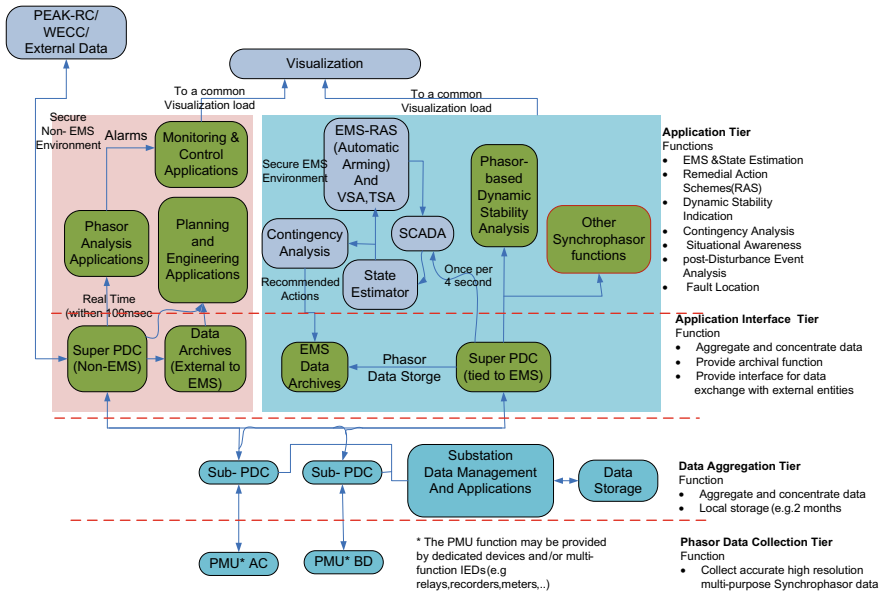
Fig. 57.2 Conceptual architecture of synchrophasors based wide area monitoring system

57.3.1   *Phasor Measurement Units*

PMUs are an electronic system to use digital signal conversion technique to measure AC waveforms and transfer them into phasors using global time synchronization signal from global positioning system (GPS).Internal architecture of PMU is shown in Fig. 57.3. The main components of PMU include [14, 15].
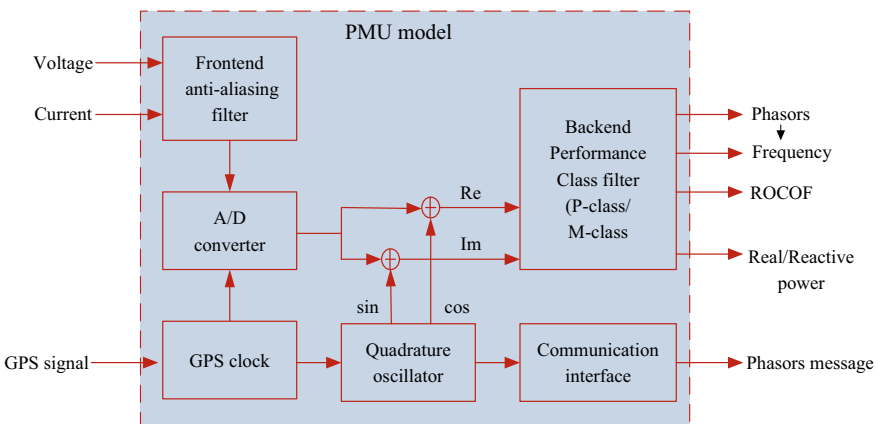

Fig. 57.3 PMU architecture

i.   Sensor module: It comprises of current transformers (CTs) and voltage transformer (PTs).The three-phase current and voltage signals are applied to analog-to-digital converter through CT and PT modules, which convert their values in a range suitable for processing the input voltage and current.

ii. PMU module: All the electronic circuitry and processing unit comes under PMU module. It estimates the phasor value from the sampled data at the input. The sampling rate of the input data is quite high and varies from 24 to 64 samples per cycle. The selection of algorithm for phasor estimation is user defined which could be discrete Fourier transform (DFT), Kalman filtering, etc. Usually, DFT is used in commercially available PMUs. The phasor reported by the PMU module varies from 25 to 60 frames per second.

iii. GPS receiver: It generates 1 pulse per second (pps) signal with time tag and contains the time information of the local area at UTC where PMU is to be installed.

iv. Standard protocol: The latest PMU protocol is IEEE C37.118 of 2011, which replaces the IEEE C37.118 protocol of 2005. The first PMU protocol was IEEE-1344 of 1998. The first PDC protocol was IEEE C37.242, introduced in 2013. These protocols define standards for data to phasor conversion, data synchronization, input/output timing formats, etc.

57.3.2   Sub/Local Phasor Data Concentrator

They align the phasor data achieving from multiple locations installed with PMUs to capture the coherent picture of the system [15]. They store the PMU data locally and send it to super PDC installed at control center.

57.3.3   Communication Network

It is required to transfer huge data from PMUs to the PDC/control centers. The performance of WAMS containing huge amount of data heavily rely on fast, reliable and secure communication system. It help in developing suitable control action to mitigate the faulty conditions. The various options available for efficient data transfer are microwave, telephone lines, satellite, power line communication, optical fiber, etc. Fiber optic cable is widely accepted for this purpose due to its wide bandwidth, fast propagation speed, and immune to electromagnetic interference [16].

57.3.4 Super PDC

Super PDC is used for time aligning huge dataset aggregating from PMUs and local PDCs. It can simultaneously store and send PMU data to multiple locations. By using multiple PDCs, customer can create multiple layers of concentration, within a synchrophasors data system. It is located at central location of the power grid such as transmission system control center [15].

57.3.5 Synchrophasors Based Application or Tools

Once the coherent picture of the entire grid is obtained at the central PDC, some application tools are required to perform certain functions like power flow analysis, load scheduling, load forecasting, fault location, contingency analysis, etc.

57.4 Synchrophasors Applications

Synchrophasors technology enables the advantage of efficient resolution to substantially improve transmission system planning maintenance, operation, and energy trading. Synchrophasors can give precise grid operating states. They can give enhanced computation of power flows, allowing higher power transfer and reduced crowding payments [6, 17, 18]. Need of synchrophasors includes.

(1) To obtain high resolution data.
(2) The data from various locations using SCADA system are not apprehending at the same instant time.
(3) Support system operators to be more aware about grid operating states.
(4) Achieve power quality.
(5) Frequency changes, MW, MVAR-measurement.

These applications are classified as:

57.4.1 Real-Time Control and Monitoring:

Real-time control and monitoring assistance enable the power grid to remain under safety margins in the event of fault, while operating close to its limits. A power system equipped with PMUs enable it to operate at higher capacity, best economics, and enhanced accuracy. Various monitoring and control applications that a WAMS offers in the modern power system are summarized in Table 57.2 [19].

Table 57.2 Real-time and off—line description

WAMS application	Description
Real-time (situational awareness improvement)	Visualization/ contorting of magnitude as well as the angle of all three current/voltage phasors, angular, frequency, the separation between pair
Off-line (low, frequency oscillations)	Finding of amplitude, duration, time, type, nature, frequency
Off-line (post-dispatch analysis of network operation)	Validation of generator grouping based on slow coherency, steady-state dynamic state detail model, detection of islanded network synchronization, and substation disturbances
Off-line (post-mortem analysis of faults)	Finding of all types of errors, fault clearing time and location, nature and time of errors, successful and unsuccessful system reclosing, voltage recovery post-fault clearance

57.4.1.1 Power System Rebuilding

In case of partial or complete power system failure of a supply region, the synchrophasors estimates can help in a fast reconnection. They give the significant data for the reclosure of the circuit breakers by reporting values of the voltage, current, frequency, and phase angle. It has been experienced, after India's most massive blackout on July 30, 2012, a PMUs based WAMS can play a major role in ensuring reliable power system operation.

57.4.1.2 Enhanced State Estimation

Synchrophasors can participate in enhancing quality of SE by feeding in previous estimates. It can enhance the speed and exactness of the state estimations. Another favorable impact is that by using PMU measurements for state estimation, less estimates centers are required because of the time synchronization of measurements [20, 21].

57.4.1.3 Voltage and Angular Stabilization Control

Voltage stabilization control is one of the applications of PMU. In the power system, this application monitors a load of a line, utilizing PMU measurement at the two ends. In any case, observing the variation of the voltages gives a good overview of system responses.
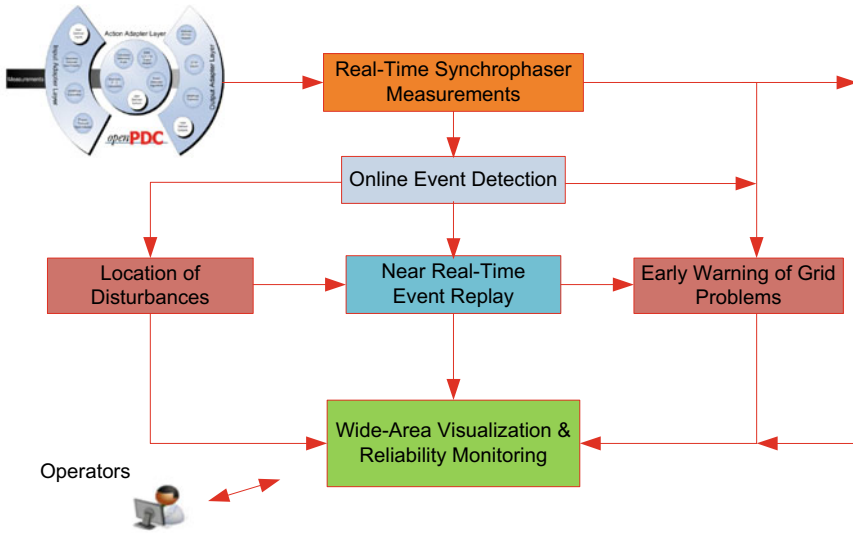
Fig. 57.4 Situational awareness system

57.4.1.4 Post-Mortem Analysis of Disturbances and Fault

The requirement of analysis after a fault is quite important to study the effects of faults on the system. With these fault recorder data, the root causes of power system events can be determined. It enables the grid operator to discover the reason for the aggravation of fault. This application can be also useful for distribution system also [22].

57.4.2 Situational Awareness Coordination

57.4.2.1 Situational Awareness

This application has been developed to give wide-area systems deep insight of power system behavior and give early warning to the potential power system events and hence raise the situational awareness of the grid operator. The flowchart for such a system is shown in Fig. 57.4 [23].

57.4.2.2 Frequency and Angle Monitoring

Utilizing PMU measurements for frequency and angle estimation is a general feature of such a system to improve the observability of electric grid. It can also be useful

in distribution systems in light of the fact that the functions they have to perform are much more complex compared to transmission system. This is because of the presence of large intermittent renewable energy resource. These measurements are quite helpful in developing plenty of application for proper functioning of smart grid [24, 25].

57.4.3 Analysis/Estimate Planners

57.4.3.1 Baselining Power System

Using this application with significant grid state data can provide several key indicator for performance of the grid.

(1) Computing system performance index

- Oscillation detection damping ratio, oscillation frequency, its duration, classification, and source of location
- frequency index performance (e.g., the size of generation before blackout and its frequency, steep frequency, solution, time of the blackout)
- power-angle stability
- voltage stability indicator

(2) Power system measurements that better sign system stress

- power flow on key lines
- total generation correlation
- reactive power reserves
- generator group
- phase angles

57.4.3.2 Post-Event Analysis

The huge amount of PMU data stored in the phasor data concentrator can be used to conduct analysis of events that introduces instability in the power system. Every user can choose any of these events to conduct the post-event examination by exchanging the related event information from the event database to the clients' computer so that client can begin the event analysis when the main segment of the event information is accessible. This is one of the most important aspect of WAMS since it enables the grid operator to understand several potentially dangerous grid events [26, 27].

Table 57.3 Time requirement-based synchrophasors application

Time	Application
Fast (0–5 min)	– Stability of frequency – Out of step confirmation – Automatically arming of the fixed work program – Low-term passing stability
Short-term (5 min-1 h)	– Short signal stability control – Voltage stability control/estimates – Model efficiency – State estimation
Long-term (1 h)	– Achievement controlling and trending – Designing abnormality alarming – Baseline natural phase angle direction – Phasor network achievement test and data type

57.4.3.3 Modal Analysis

Modal analysis is performed on synchrophasors data to determine angular between several generator groups to distinguish prevailing between various oscillations modes present in the system. It includes determination of frequencies, damping rate, and mode shapes (showing whether two generate swing together or against each other) [28].

57.4.3.4 State Estimation

SE performs many power system application such as power flow analysis, security assessment load forecasting SE can achieve, etc. This solves that requires past, present, and available redundant measurements. The accuracy of SE depends on the assumed system model and hence the estimation of the states highly rely on the robustness of the system model [16, 29, 30].

The various performance indicator on which the robustness of SE rely are accuracy, robustness against measurement and modelling noise, speed of computation, and scalability.

Of all the applications discussed, they are further classified based on the time required by them to complete the task provided. Hence, based on time required, these applications are classified as fast, short-term, and long-term applications and are given in Table 57.3.

57.5 Case Study NR of Indian Power Grid Using Synchrophasors Data

For analyzing application of synchrophasors in the power system, a case study of the event during fog condition of PMUs at Meerut and Hissar is caused out. The PMUs data helps in monitoring significant tripping in NR that enabled the grid operators to have best situational awareness about the grid operating states. This helps in identifying more cases of multiple tripping, blackout due to flashover under heavy fog condition through many previous years. This problem is increased in recent years due to increase in pollution level and may result in black out in large parts of the grid for many hours. These problems usually occur mid-night and early morning while the atmospheric temperature is low and relative humidity is high, and the situation appropriates for fog formation. In this analysis, PMU plots were taken on an hourly basis at Meerut and Hissar. These plots were time stamped with different tripping instants mentioned with the screenshots, which enhance situational awareness of the power system grid operator. Figure 57.5 describes tripping for the times (20:50–21:50 h), (01:00–02:00 h) and (02:15–03:15 h). This happen at Muzaffarnagar and Muradnagar, Kaithal, Panki substations, and Roorkee. Several instances of Auto Recloses were also captured in the events. It can be tackled by regulating the generator load. In Fig. 57.6, positive sequence voltage between Meerut and Bassi shows failure in auto reclosure attempt of 400 kV line, between Meerut and Muzaffarnagar. In Fig. 57.7, PMU captures positive sequence voltage between Moga and Bassi and has successful auto reclosure attempt of 765KV line between Moga and Bhiwani [31, 32].
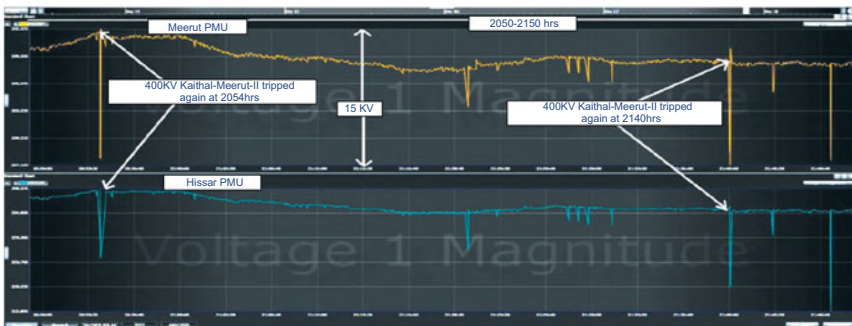

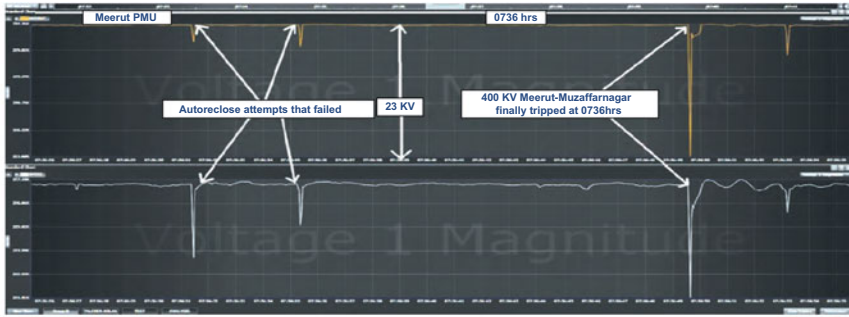**Fig. 57.5** Positive sequence voltage plots of Meerut and Hissar PMU (20:50–21:50 h)

Fig. 57.6 Positive sequence voltage plots of Meerut and Bassi PMU (failed Auto reclosure of 400 kV Meerut-Muzaffarnagar)
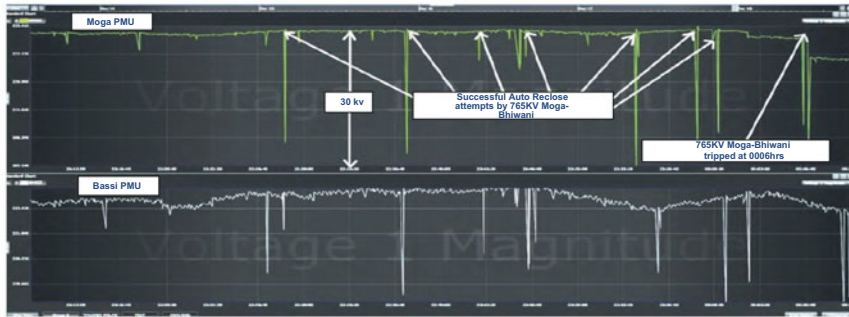

Fig. 57.7 Positive sequence voltage plots of Moga and Bassi PMU (successful Auto reclosure of 765 kV Moga-Bhiwani)

57.6 Conclusion

This paper highlights the importance of synchrophasors based wide area monitoring system in improving the situational awareness of grid operators of modern power system. Various applications that the synchrophasors based WAMS offer to the grid are discussed. These includes real-time monitoring and control, fault detection and isolation, modal analysis, load scheduling, state estimation, etc. A case study is also presented highlighting the utility of such a system in detecting and isolating the fault under worse operating conditions.

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