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A COMPREHENSIVE REVIEW OF WIDE-AREA MONITORING AND CONTROL SYSTEMS IN MODERN POWER GRIDS USING PHASOR MEASUREMENT UNITS

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Abstract

Modernization of the power system leads to more complexity and intricacy of the power grid operations as a result of renewable power source incorporation, distributed generation, advanced smart grid techniques, and dynamic changes of loads. The problem with conventional SCADA systems is that they lack the capability to give the necessary time resolution for the real-time monitoring process because of the continuously changing scenario in the grid network. Phasor Measurement Units (PMU), on the other hand, have become an innovative tool for the Wide-Area Monitoring, Protection, and Control (WAMPAC) process using GPS technology. Time-synchronized measurements of the voltage and current phasors are achieved with high speed thanks to PMUs. As a result, the monitoring of the situation on the grid, state estimation, oscillation monitoring, voltage stability estimation, and adaptive protection become much easier. This article gives an overview of the existing state of the art concerning Wide-Area Monitoring and Control Systems (WAMCS) based on PMUs implemented in contemporary power grids. Architecture, communication channels, applications, benefits, challenges, and development of WAMCS systems with PMUs are discussed in detail.

Keywords: Phasor Measurement Unit (PMU), Wide-Area Monitoring System (WAMS), Smart Grid, Synchrophasor Technology, Power System Stability.

1. Introduction

Power grid can be regarded as one of the most important infrastructures without which it would be difficult for our society to function as it currently does, since it is constantly providing electricity for households, companies, and businesses. Modern power grids have become increasingly complicated as compared to the relatively simple structures of the earlier periods due to their development from simple centralized systems [1]. An increasing demand for electricity, involvement of renewable energy resources in the structure of the power grid, the emergence of distributed generation systems, and smart grids have created numerous difficulties with the functioning of the power grid. Thus, it is required to use advanced methods for controlling and protecting it.

1.1 Background of the study

The existing situation in the world's power industry shows a shift that has occurred because of technical innovations and changes in the pattern of energy consumption. The growing presence of renewable energy sources results in increased variability and uncertainty in the functioning of power grids [2]. On top of that, the increased prevalence of distributed generation, microgrids, EVs, smart devices, and the like makes it difficult to manage the operation of power grids. In order to deal with this new challenge, utilities need to constantly monitor the parameters of power systems.

Up until now, power system monitoring involved the use of Supervisory Control and Data Acquisition (SCADA) systems. Although SCADA has been used in the power sector for decades, it provides measurements at slow sampling rates and cannot be used to analyze transients and instabilities in the operation of power systems [3]. As such, traditional monitoring methods prove insufficient when applied to modern and increasingly complex power systems.

PMUs have been developed to tackle this problem. Unlike traditional solutions, PMUs allow obtaining synchronized measurements of voltage and current phasors using GPS timing signals. High-speed synchronized measurements made possible the design and implementation of WAMS (Wide-Area Monitoring Systems) and WAMCS [4].

1.2 Objectives of the Review

The objectives of this review are:

- To examine the principles and operation of PMUs.
- To analyze the architecture of WAMCS.
- To evaluate applications of PMUs in modern power systems.
- To discuss challenges and future research directions.

2. Fundamentals of Phasor Measurement Units

PMUs have turned out to be one of the most remarkable technological innovations in modern power system monitoring and control. With PMUs, measurements of electrical parameters can be made from synchronized sources at various geographical points, and hence providing more insight into the operations of the power system. Unlike other traditional measuring instruments, the PMU takes advantage of precise time synchronization from the GPS in measuring the voltage and current phasors at different points in the power system. This technology is the basis of the WAMS/WAMCS systems that ensure reliability and stability of modern power systems [5].

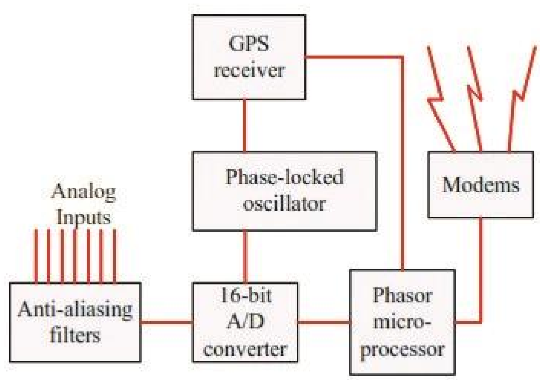

Figure 1: Internal Architecture of a Phasor Measurement Unit (PMU)

2.1 Concept of Synchrophasors

Synchrophasors refer to time-stamped values of electrical waveforms which capture the magnitude and phase angle of voltage and current values in a power system relative to a common time reference. This time synchronization is mainly provided by GPS clock signals which make it possible to correlate measurements made at various points within the grid.

The idea of synchrophasor measurement came up to overcome the problems associated with nonsynchronized power system measurements. Prior to the introduction of synchronous measurements, there was no common time reference hence making it impossible for operators to have a complete picture of the dynamic performance of the system in case of any disturbance.

The significance of time-synchronized measurement of power systems comes from the fact that they help in analyzing various types of dynamic events like oscillation, voltage instability, frequency changes and power swings among others [6]. This makes it possible to make use of synchronized measurement values in applications like state estimation, stability studies, disturbance studies, adaptive protection, and wide area control of the system.

A synchrophasor is a waveform whose magnitude and phase angle values are represented with respect to time, which gives the accurate value of the amplitude and the position of the signal being measured with regards to a reference time value. This time synchronisation usually involves the use of GPS clock signals [7].

A sinusoidal voltage waveform can be represented as:

$$v(t)=V_m\cos(\omega t+\phi) \qquad (1)$$

where V_m is the peak voltage magnitude, ω is the angular frequency, and ϕ is the phase angle.

The corresponding phasor representation is expressed as:

$$\mathbf{V}=V_{rms}\angle\phi \qquad (2)$$

where V_{rms} denotes the root mean square (RMS) magnitude and ϕ represents the phase angle. PMUs measure and synchronize these phasors using a common GPS time reference, enabling accurate comparison of electrical quantities across geographically dispersed locations.

Table 1. Comparison Between SCADA and PMU Systems

Parameter	SCADA	PMU
Sampling Rate	Every 2–10 seconds	30–120 samples/sec
Synchronization	No global synchronization	GPS synchronized
Dynamic Monitoring	Limited	Excellent
State Estimation Accuracy	Moderate	High
Situational Awareness	Low	High
Response Time	Slow	Real-time

2.2 PMU Architecture

A Phasor Measurement Unit consists of several hardware and software components that work together to acquire, process, synchronize, and transmit electrical measurements. The architecture of a PMU is designed to provide highly accurate and time-synchronized phasor measurements suitable for real-time monitoring and control applications.

- **Voltage and Current Transformers:** The first component of the PMU is made up of instruments called instrument transformers, which include voltage transformers (VT) and current transformers (CT). This component acts to transform the high-voltage and high-current signals into low-voltage and low-current levels that are measurable by electronics while still being accurate.
- **GPS Synchronization Module:** The GPS synchronization module is the source of time in the PMU. Using the signals transmitted by GPS satellites, the PMU can align itself with other PMUs installed at other sites on the network. The synchronization process has an accuracy of a microsecond, enabling comparisons of data collected at various sites.
- **Analog-to-Digital Converter (ADC):** The analog values generated from the voltage and current transformers are then digitized using an Analog-to-Digital converter. The process involves sampling of the input waves at high speeds to generate corresponding digital data that can then be used by the PMU for calculations.
- **Phasor Estimation Algorithms:** The data are processed using phasor estimation algorithms to estimate the magnitude, phase angle, frequency, and ROCOF. Such algorithms make use of methodologies such as DFT, FFT, or sophisticated techniques to ensure accurate readings.

2.3 Working Principle of PMUs

PMU operation entails the following series of operations where raw electrical signals are converted to synchronized phasors suitable for wide-area monitoring and control.

- **Acquisition of Signals:** Continuous acquisition of voltage and current analog signals is done in a PMU by instrument transformers in the power system. This involves sampling of the instantaneous electrical quantities in the system.
- **Time synchronization:** After acquisition, signal time synchronization occurs in the PMU using the timing data obtained from GPS satellites. Precise timestamping of each measurement enables correlation of the measurements between multiple PMUs.

- **Calculation of Phasors:** Synchronized signals are subjected to calculations using phasor estimation techniques to obtain the phasor magnitudes and angles of the voltage and current waveforms. Alongside the phasor data, frequency and rate of change of frequency are calculated as well.
- **Transmission of Data:** Synchrophasor data generated after the calculations are then encapsulated into standard format messages and transmitted to Phasor Data Concentrators and control centers to be used in various applications such as state estimation, oscillation monitoring, faults, and wide-area control systems.

2.4 PMU Standards

Standardization is essential to guaranteeing interoperability, reliability, and precision of the PMU-based monitoring system. There are some standards established internationally on synchrophasor measurements and their communications.

- **IEEE C37.118.1:** The IEEE Standard C37.118.1 is associated with performance criteria of synchrophasor measurements. The required parameters involve measurement accuracy, report rate, dynamic response of measurement, frequency measurement, and tests of synchrophasors measurements. According to those parameters, the IEEE Standard C37.118.1 guarantees reliable and consistent result of PMU measurements.
- **IEEE C37.118.2:** Communication protocols and data transfer related to synchrophasors are involved in IEEE C37.118.2 standard. This standard covers the issues of message form, data structure, communication procedures, and network necessary to transmit synchrophasor data among PMU, Phasor Data Concentrator, and control center. Following this standard is helpful to increase interoperability among the products of different manufactures.
- **IEC 61850 Standards:** The IEC 61850 standards refer to communication networks and systems of electrical substations. As mentioned above, IEC 61850 standards support high-speed communication and interoperability of intelligent electronic devices (IED). In particular, PMU falls into this kind of devices as well. Synchrophasor technology can be applied in modern digital substations thanks to IEC 61850.

Table 2: review of literature on PMU-Based WAMCS

Author(s) & Year	Study Focus	Key Findings	Relevance to Section
Ashok, V., Yadav, A., & Abdelaziz, A. Y. (2020) [8]	Comprehensive review of Wide-Area Protection, Control, and Monitoring Systems (WAPCMS)	Underlined the significance of synchronized measurement, communication facilities, and sophisticated protection system for improving the reliability of the power grid.	Supports discussions on WAMCS architecture, protection schemes, and PMU applications (Sections 3, 4, and 5).
Maheswari, M., Suthanthira Vanitha, N., & Loganathan, N. (2020) [9]	Wide-Area Measurement Systems (WAMS) and PMUs	Covered operation mechanisms of PMU, synchrophasors measurements, communication models, and monitoring uses.	Supports PMU fundamentals and architecture (Sections 2 and 3).
Monti, A., Muscas, C., & Ponci, F. (2016) [10]	PMU technologies and Wide-Area Monitoring Systems	Gave thorough knowledge about the design of PMUs, standards, and accuracy of measurement.	Supports PMU concepts, standards, and monitoring applications (Sections 2 and 4).
Biswal, C., Sahu, B. K., Mishra, M., & Rout, P. K. (2023) [11]	Real-time grid monitoring and protection using PMUs	Showed the benefits of PMUs in state estimation, fault location, oscillation monitoring, and protection.	Supports applications of PMU-based monitoring and protection systems (Sections 4 and 5).

Pazderin, A., Zicmane, I., Senyuk, M., Gubin, P., Polyakov, I., Mukhlynin, N., et al. (2023) [12]	State-of-the-art review of PMU applications in modern power systems	Discovered new uses for PMUs in grid monitoring, integration of renewable energy, stability assessment, and smart grids.	Supports PMU applications, smart grids, and future developments (Sections 4, 6, and 7).

3. Architecture of Wamcs

WAMS is a highly advanced technological system capable of monitoring, analyzing, securing, and controlling power systems on a large scale. The complexity of today's electrical networks, fueled by the incorporation of renewable energy sources, distributed generation, and varying loads, has made it mandatory to use monitoring systems that can capture the status of such systems with great precision and fast reaction time [13]. Wide area monitoring is achieved using PMU-based synchronized data acquisition throughout extensive geographical areas.

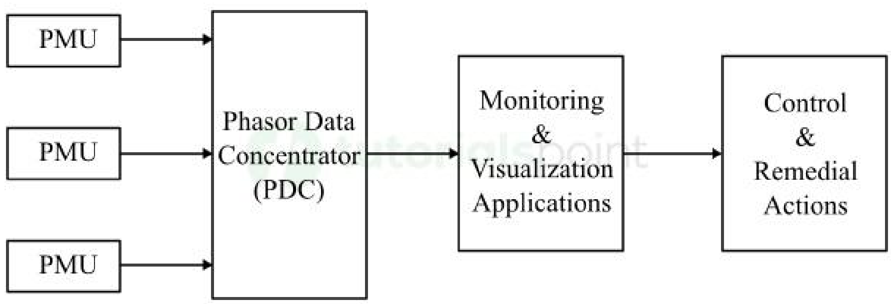

Figure 2: Data Flow Architecture of a PMU-Based Wide-Area Monitoring System

3.1 WAMCS Framework

The Wide-Area Monitoring and Control System framework comprises several key components that facilitate the acquisition and utilization of synchronized measurement data throughout the power network.

- PMUs: Measure voltage, current, frequency, phase angle, and ROCOF of the electrical grid in real time.
- Communication Network: Transfers information gathered by PMUs through communication channels to processing centers.
- Phasor Data Concentrators (PDCs): Synchronizes, validates, and aggregates information collected from several PMUs before transferring it to be processed.
- Control Centers: Monitors, analyzes, and interprets synchrophasor information obtained from the PMUs for decision-making purposes.
- Decision Support Systems (DSS): Processes synchrophasors' data utilizing algorithms and makes appropriate decisions regarding control actions.

3.2 Data Flow in WAMCS

The effectiveness of a Wide-Area Monitoring and Control System depends on the efficient flow of synchronized measurement data from acquisition points to monitoring and control applications. The general data flow within a WAMCS follows the sequence:

PMU → PDC → Control Center → Monitoring and Control Applications

First, PMUs deployed throughout the power grid capture synchronous measurements of voltages and currents. Each captured measurement is then stamped with time and sent through the communication network to at least one Phasor Data Concentrator.

Then, synchronization of data acquired from the PDC is carried out on the basis of the time stamps of data. PDCs synchronize data, discard inaccurate data, and conduct initial validation of the data and then transmit data to the control center [14].

Finally, the control center collects synchronized data from several PDCs and analyzes them using specialized applications. These applications assess the current state of the system, detect any abnormalities within it, and produce information to help control operators understand the current situation.

3.3 Communication Infrastructure

The communication infrastructure is an essential part of WAMCS as the efficiency of wide area monitoring largely relies upon the timely and effective delivery of synchrophasor information. In this regard, the communication network has to ensure high-speed data delivery along with low latency and high availability.

- Fiber Optics Communication: Possesses higher bandwidth, lower latency, good reliability, and immunity to electromagnetic interference; therefore, considered an ideal technology for the transmission of PMU data.
- Wireless Communication: Facilitates flexible and economical means of data transmission using wireless technology such as microwave communication, cell phone networks, satellite, and wireless sensor networks, especially in remote locations.
- Internet Protocol (IP) Communications: Allows for standardization of communications, interoperability between devices, smooth integration into current utility infrastructure, and deployment of monitoring systems.
- 5G Communication Technologies: Ensures very low latency, high bandwidth, high reliability, and huge connectivity capacity, making it suitable for real-time monitoring and smart grid applications.
- Overall Functionality: All the above mentioned communication techniques facilitate effective and secure exchange of synchrophasor data in WAMCS systems.

3.4 Synchrophasor Data Management

Large deployments of PMUs result in huge amounts of synchrophasor data. This necessitates efficient management of the data to derive maximum benefit from the application of WAMCS.

- Data Aggregation: It involves collecting, synchronizing, and aggregating the synchrophasor measurements made by various PMUs in order to form a single data flow for the system analysis.
- Storage Systems: Storage systems include cloud computing systems, distributed database, and other big data technology solutions in order to facilitate the storage of synchrophasor data.
- Real Time Analytics: This process involves analysis of the incoming data for detecting any anomalies, oscillation, system stability, predicting failure, and performing the appropriate actions.
- Technologies: Technologies such as artificial intelligence (AI), machine learning (ML) and data mining algorithms are being increasingly used to improve the process of analyzing the data.
- Overall Functionality: Proper management of the data will ensure effective analysis and use of synchrophasors in improving the functionality of WAMCS.

Finally, the design of WAMCS involves utilization of PMUs, communication network, PDCs, control centers, and decision making tools in order to achieve an integrated solution to the problem of monitoring and controlling the power system [15]. The use of efficient communication networks and advanced synchrophasor management techniques can prove to be vital in harnessing the benefits of synchronous measurements [16].

4. Applications of Pmu-Based Wide-Area Monitoring Systems

The adoption of PMUs in the monitoring of modern power systems has been beneficial as it enables fast measurement which increases the reliability, stability, and security of electrical networks. Some of the key uses of WAMS include state estimation, monitoring of oscillations, voltage stability, frequency monitoring, disturbance analysis, and situational awareness. All these uses of WAMS give power system operators an opportunity to get more information on the system state, enabling proper decision-making [17].

One of the areas where PMUs have brought a lot of improvement is state estimation. This is made possible due to enhanced observability and accurate measurement of voltage magnitudes and angles. Inter-area oscillations can be detected easily and effectively. PMUs also make small-signal stability analysis possible to ensure that the power network is stable and there will be no disturbances. Voltage stability can be achieved since the system can detect any changes that may lead to voltage collapse. Frequency monitoring helps achieve a balance between supply and demand [18].

Table 3. Applications of PMU-Based WAMS

Application	Purpose	Benefits
State Estimation	Determine system state	Improved observability
Oscillation Monitoring	Detect oscillations	Enhanced stability
Voltage Stability Monitoring	Prevent voltage collapse	Early warning capability
Frequency Monitoring	Maintain system balance	Improved reliability
Disturbance Analysis	Analyze faults and events	Faster restoration
Situational Awareness	Support operators	Better decision-making

5. Wide-Area Protection and Control Using Pmus

Modern power grids are becoming increasingly more complex due to higher dependence on renewable energy sources, making it necessary to develop new ways of protecting the grid against sudden system disturbances [19]. Conventional methods of protection may be unable to provide an overview of system dynamics, since they depend on local observations only. With the introduction of PMUs, the concept of Wide Area Protection and Control was born, allowing for protection and control through synchronized measurements at several geographic locations [20].

5.1 Wide-Area Protection Schemes

A wide area protection scheme employs measurements that are synchronized using PMUs to determine any abnormal state in order to implement protective actions in the whole power system. Wide area protection scheme provides a bigger picture than a conventional protection scheme, and hence facilitates better action against major disturbances. Examples of wide area protection applications include adaptive protection and System Integrity Protection Scheme (SIPS) [21].

5.2 Adaptive Relaying

One way of ensuring the proper protection of electrical networks is through the use of adaptive relaying where the relays are set depending on the system's operating state. The use of PMUs is vital in providing timely information required for adaptive relaying. Important features of adaptive relaying include dynamic adjustment of relay setting values and enhanced fault discrimination.

5.3 Controlled Islanding

Controlled islanding is one of the crucial emergency control methods that allow maintaining the stability of the power system under adverse conditions [22]. The idea of the process consists of deliberate separation of an interconnected electrical grid into several independent islands to avoid catastrophic system failure. PMU monitoring facilitates controlled islanding by providing timely analysis and making necessary decisions. Some major aims include avoiding cascading failure and improving the grid resilience [23].

5.4 Load Shedding Applications

Load shedding is a common method of regulation employed in order to ensure stability in case of deficiencies in power generation or voltage instabilities. Wide area monitoring systems based on PMUs give accurate and reliable information for effective load shedding actions. Some common methods of load shedding include underfrequency load shedding and voltage load shedding [24].

5.5 Emergency Control Systems

The emergency control systems operate quickly to counteract emergencies that jeopardize the security and reliability of power systems. With PMU, wide area monitoring systems can offer the needed situational awareness required in emergency control applications. This type of system is used in different applications to prevent blackouts and assist in their restoration.

In conclusion, wide area protection and control systems based on PMU technology have been integrated as vital tools in modern power systems. With PMUs incorporated in the control systems, power utilities will be able to provide more secure and reliable power systems.

6. Pmus in Smart Grids and Renewable Energy Integration

The evolution of electricity networks has contributed to the development of smart grids featuring communication systems, control systems, distributed energy resources, and automation systems. In the new landscape, the deployment of PMUs has been vital in delivering precise, real-time measurements. The use of PMUs has allowed power providers to achieve better insights into the performance of electric grids. The integration of PMUs into smart grid systems allows electric utility companies to gain more information about their networks, which can be used for advanced management purposes [25].

PMU technology is vital in numerous applications associated with smart grids since it allows for the delivery of timely and synchronized measurements. Another important issue related to the future developments in power grids is the increase in the use of renewable energy resources like wind energy and solar energy. PMU measurement systems play an important role in addressing some challenges linked with renewable energy generation.

Apart from their application in the grids on large scales, the PMUs have greatly impacted the monitoring and control of the microgrids that can be either standalone or work alongside the main utility grid. The fast data gathering of the devices makes it possible to ensure efficient power management, stability analysis, and a smooth switch-over between both grid-tied and stand-alone modes of functioning. Furthermore, the increasing popularity of electric vehicles in recent years requires new operational conditions to be met by power systems through proper loading, charging, and analysis of their impacts. Here the fast data gathering is very helpful for managing the EV integration process.

Among the most popular applications of the devices in this area are Smart Grid Applications, Renewable Energy Integration, Microgrid Monitoring and Control, and Electric Vehicle Integration.

7. Conclusion

PMUs have brought about significant changes in WAMCS in today's power networks through synchronized measurements of high resolution that improve awareness, reliability, and resiliency in power networks. The utilization of PMUs in Wide Area Monitoring and Control Systems allows for enhanced functions such as state estimation, stability analysis, adaptive protection, and decision-making. Although there exist some problems concerning cost, communications, data handling, and security issues, further innovations in AI, cloud computing, Internet of Things, and digital twins have continued to boost the performance of PMU-based systems. Future smart grids will require more PMU monitoring and control systems for their operation.

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