Prospects for Situational Awareness of Power Systems Using Phasor Measurement Units (PMUs) in Nigeria

[1]Tasiu S.G. Wudil, [2] Lasisi S. Lawal, [3] Y. S. Haruna, 4 G. A. Bakare, [5]O. U. Aliyu, [6]Francis A. Adedeji.
Electrical and Electronics Engineering Department, School of Engineering and Engineering Technology
Abubakar Tafawa Balewa University Bauchi, P. M. B. 0248, Bauchi, Nigeria
twudil@ieee.org; 2 lasisi.slawal@udusok.edu.ng; 3 ysharuna@atbu.edu.ng, 4 gabakare@atbu.edu.ng;
5 uoaliyu@yahoo.com

ABSTRACT

Maintaining the stability and reliability of power grids is critical, and situational awareness (SA) is a key element in achieving such in power systems. Adopting Phasor Measurement Units (PMUs) in providing real-time monitoring and control of power systems is fundamental, sustainable, efficient, and commendable. This paper presents a comprehensive overview of PMU technology, its role in enhancing SA, and its impact on improving power system stability and efficiency. PMUs are sophisticated monitoring devices that offer high-speed and synchronized voltage and current phasors measurements: This enables power systems to be monitored and controlled in real-time. Our discussion covers the fundamental principles of PMU technology, its various applications, its implementation in power systems, and the challenges and limitations of its use. In addition, the paper explores current and future research on PMUs and highlights the benefits of their implementation, including enhanced reliability, improved security, better power quality, and increased efficiency. Through a detailed presentation of the capabilities and advantages of PMUs in power systems, we offer valuable insights for researchers, practitioners, and decision-makers in the power industry.

1. INTRODUCTION

Situational awareness (SA) can be defined as the cognizance of entities in the environment, understanding their meaning, and the projection of their status in the near future, (Munir et al., 2022). Situational awareness refers to the ability to perceive and understand the current state of a system and to use this understanding to make effective decisions and take appropriate actions,(Endsley, 1995). In power systems, situational awareness is critical for ensuring the reliable and efficient operation of the grid, as well as for responding to emergencies and other contingencies. Modern power systems' increasing complexity and dynamic nature makes it challenging to use traditional methods alone to maintain situational awareness.

Phasor measurement units (PMUs) have emerged as a promising technology for enhancing situational awareness in power systems,(A. G. Phadke and J. S. Thorp, n.d.). PMUs measure voltage and current waveforms' phasors (magnitude and phase angle) at high sampling rates (typically 30 to 60 samples per second). These measurements provide a real-time view of the state of the power system, allowing operators to detect and respond to disturbances and other events quickly.

PMUs for situational awareness have become increasingly widespread in recent years, with many utilities and grid operators deploying PMU networks across their systems, (Sihag & Tajer, 2018a). PMU data can be used for various applications, including system monitoring, fault detection and location, and dynamic performance assessment,(Sihag & Tajer, 2018b). The availability of high-quality PMU data has also enabled the development of advanced analysis tools, such as state estimation and visualization software, that further enhance situational awareness in power systems.

1.1 POWER SYSTEMS

Power systems refer to the networks of generators, transformers, transmission lines, and distribution lines that form the backbone of our modern electrical grid. These systems deliver electricity from power plants to homes, businesses, and consumers. Power systems are designed to be reliable and efficient. Still, they can also be vulnerable to disruptions and failures due to various factors, such as extreme weather events, equipment failures, and cyber-attacks. As a result, ensuring the safety, reliability, and resilience of power systems is crucial for modern society. Figure 1 is a typical schematic of a Power System depicting the generation, transmission and distribution networks.

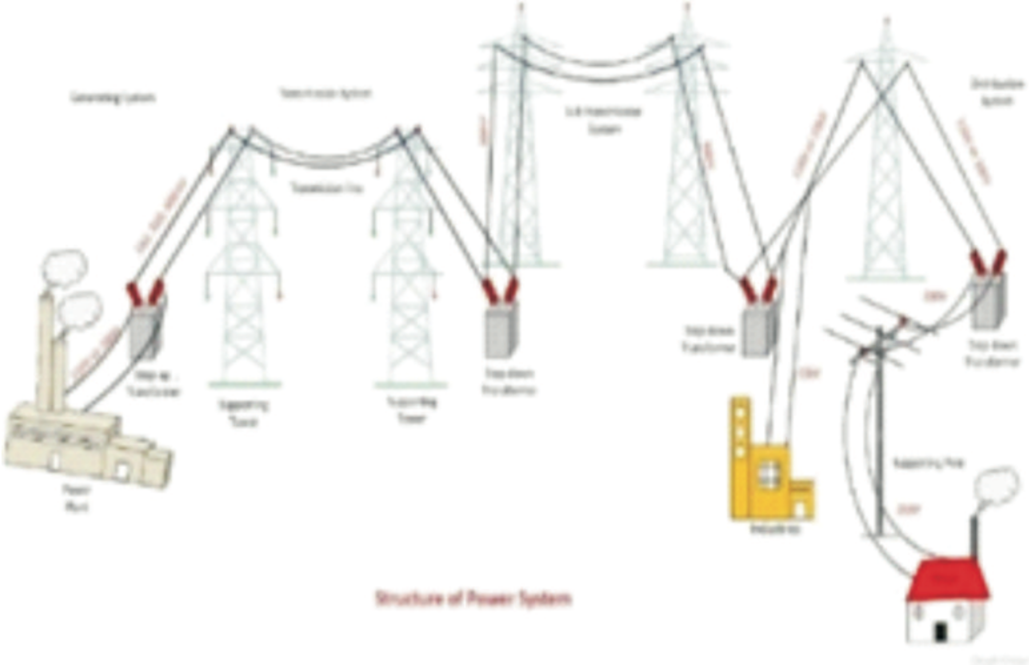

Figure 1: Structure of Power System

1.2 UNDERSTANDING PHASOR MEASUREMENT UNITS (PMUs)

Phasor Measurement Units (PMUs) are advanced monitoring devices used in power systems to measure the voltage and current phasors at different points in the network,(Bose, 2019). PMUs provide high-speed and synchronized measurements, enabling real-time monitoring and control of power systems,(Arunkumar et al., 2022). Unlike traditional measurement devices such as supervisory control and data acquisition (SCADA) systems, which typically sample data at lower frequencies and provide limited visibility, PMUs offer more comprehensive and accurate information about the power system's behaviour,(Khan et al., 2016) . GPS technology is often integrated into PMUs to timestamp the measurements accurately. GPS allows for precise data synchronization from different PMUs and helps detect and locate faults in the network, (Yang et al., 2019).

PMUs measure phasors by utilizing the principle of phasor estimation, which involves the estimation of the phasor magnitude and phase angle from the time-domain waveform. This estimation is done by applying a mathematical algorithm called the Discrete Fourier Transform (DFT) to the sampled waveform data, (A. G. Phadke and J. S. Thorp, n.d.) . The measurement data obtained from PMUs can be used for various applications such as state estimation, voltage stability analysis, oscillation detection, and control. PMUs also play a critical role in enhancing situational awareness and control of power systems by providing operators with real-time information about the system's behaviour, (J. D. Glover, et al., n.d., 2008).

In recent years, the use of PMUs in power systems has increased significantly due to their numerous benefits. These benefits include improved reliability, enhanced security, better power quality, and increased efficiency,(Bose, 2019). PMUs are now being deployed across power grids worldwide, with

GPS technology, to provide more accurate and comprehensive monitoring and control of power systems,(Arunkumar et al., 2022). Different components of a PMU are shown in the block diagram below.

Figure 2 is the block diagram of a typical PMU. The PMU basically consists of the means of analogue system signals representing the electrical quantities to be measured or monitored (either from instrument transformers or sensors), Anti-aliasing filters, Analog-Digital-Converter synchronised with GPS clock through a Phase Locked Oscillator from GPS Receiver which is looped to phasor microprocessor. The outputs are connected through communication modems.

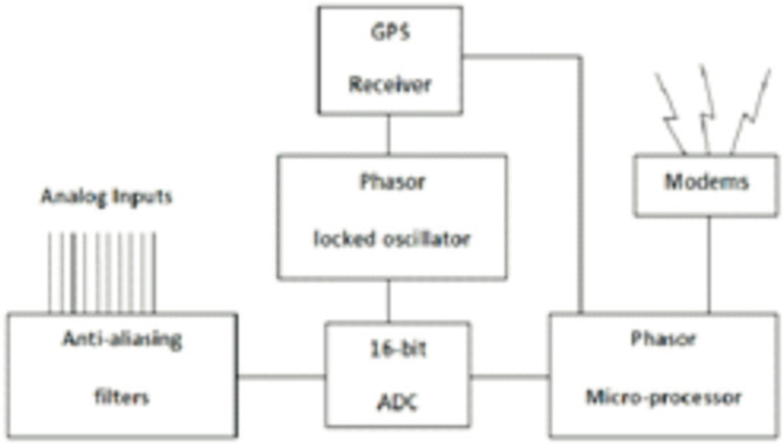

Figure 2: Component of a Phasor Measurement Unit,(Rihan et al., n.d.)

Figure 3 is a presentation of the components and communication and time signalling of the simplest PMU system without a Phasor data Concentrator (PDC).

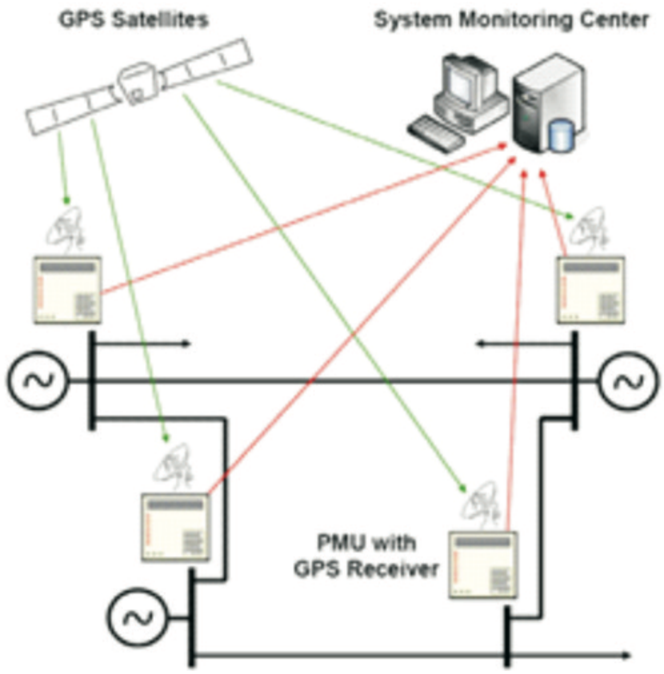

Figure 3: Principle of synchronized phasor measurements

1.3 PMUs: ENHANCING SITUATIONAL AWARENESS OF POWER SYSTEMS

Phasor measurement units (PMUs) have emerged as critical tools for enhancing the situational awareness of power systems. PMUs are advanced monitoring devices that provide high-speed and synchronized measurements of voltage and current phasors, enabling real-time monitoring and control of power systems. These measurements are utilized to identify and diagnose power system disturbances, improve power system stability, and help operate more efficiently,(Sufyan et al., 2021).

PMUs have been increasingly deployed in power systems worldwide, with many utilities using PMU measurements for real-time monitoring, control, and analysis of power systems,(Sufyan et al., 2021). Moreover, PMUs have been used to develop new algorithms for power system protection, control, and stability analysis,(Sykes et al., n.d.).

In addition, PMUs are an essential component of synchrophasor technology, which provides a new level of visibility and control of power systems. Synchrophasor technology utilizes PMU measurements to create a real-time picture of the power system. It allows operators to identify and respond to power system disturbances before they escalate into major outages,(Upadhyaya et al., 2015) .

Overall, the increasing deployment of PMUs in power systems worldwide, coupled with their ability to provide high-speed and synchronized measurements of voltage and current phasors, has enabled real-time monitoring and control of power systems, leading to improved power system stability and efficiency. Figure 4 is a typical application of PMU in a power system.

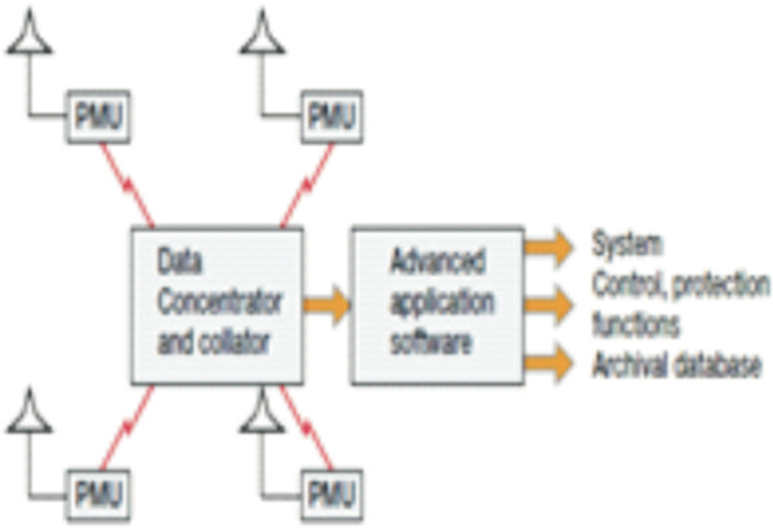

Figure 4: PMU Utilization in a Power System

1. APPLICATIONS OF PHASOR MEASUREMENT UNITS (PMUs) IN POWER SYSTEMS

Phasor Measurement Units (PMUs) measure an electrical power system's voltage and current phasors. PMUs can measure these phasors at very high speed, typically up to several thousand times per second, and with high accuracy, which makes them an essential tool for monitoring and controlling power systems.

The main applications of PMUs in power systems include:

A. Power System Stability

Power system stability refers to the ability of a power system to maintain its operating state following a disturbance or sudden change in system parameters. Stability analysis is an essential tool used by power system engineers to monitor and ensure the system's stability. PMUs play a crucial role in power system stability analysis by providing synchronized measurements of voltage and current phasors at different locations in the power system. There are two main types of power system stability:

1. Small-signal stability
2. Transient stability.

Small-signal stability refers to the ability of the system to maintain stable operation under minor disturbances, such as changes in system load or generation. On the other hand, transient stability refers to the ability of the system to recover to a stable operating point following a large disturbance, such as a fault or sudden loss of generation.

PMUs are particularly useful for transient stability analysis as they provide accurate and synchronized measurements of voltage and current phasors, which can detect and monitor any oscillations or disturbances in the system. These measurements can be used to calculate system stability margins, which indicate how close the system is to instability.

Several techniques are used for power system stability analysis, including eigenvalue analysis, time-domain simulation, and frequency-domain analysis. Eigenvalue analysis is used to determine the stability of small-signal modes of the system, while time-domain simulation is used to study transient stability. The frequency-domain analysis is used to investigate the interaction between different oscillations in the system.

PMUs have been widely used in power system stability analysis in recent years, and several research studies have investigated their effectiveness in this area. For example, a study [4] evaluated the impact of PMUs on power system stability analysis and found that PMUs could provide more accurate and reliable measurements than traditional measurement techniques. Another study demonstrated the use of PMUs in detecting and mitigating oscillations in power systems,(Upadhyaya et al., 2015).

In conclusion, PMUs are crucial for power system stability analysis, particularly transient stability analysis. They provide accurate and synchronized measurements of voltage and current phasors, which can be used to detect and monitor any oscillations or disturbances in the system. Several techniques are used for power system stability analysis, including eigenvalue analysis, time-domain simulation, and frequency-domain analysis. PMUs effectively improve the accuracy and reliability of power system stability analysis.

B. Fault Analysis

Fault analysis is a critical function in power system operation and protection. The timely and accurate detection and location of faults in the power system are essential to ensure the safety and reliability of the system. PMUs are used in fault analysis to provide synchronized and accurate voltage and current phasor measurements at different points in the power system.

PMUs provide a unique advantage in fault analysis over traditional fault detection methods, such as distance or overcurrent relays. Traditional methods provide only limited information about the fault location and may be affected by the complexity of the power system topology or fault impedance. In contrast, using synchronized phasor measurements, PMUs can detect and locate faults accurately.
PMUs can be used for different types of fault analysis, including fault detection, classification, and location. Fault detection is the process of identifying that a fault has occurred in the power system. Fault classification involves determining the type of fault, such as a three-phase, line-to-ground, or double-line-to-ground fault.

Several algorithms have been developed for fault analysis using PMUs. These include impedance-based algorithms, travelling wave-based algorithms, and model-based algorithms,(Ding et al., 2018), (Deng et al., 2020). Impedance-based algorithms use the difference in the impedance of the faulted line and the unfaulted line to determine the location of the fault. Travelling wave-based algorithms use the wave propagation time between different PMUs to locate the fault. Model-based algorithms use the power system model to estimate the location of the fault.

In conclusion, PMUs are a valuable tool for fault analysis in power systems. They provide accurate and synchronized measurements of voltage and current phasors that can be used to detect, classify, and locate faults in the power system. Several algorithms have been developed for fault analysis using PMUs, and several studies have shown their effectiveness in fault detection and location,(Abdlmnam et al., 2013),(Singh et al., 2011) .

C. State Estimation

State estimation is a process used to estimate the state variables, such as voltage and phase angle, of a power system based on the measurements obtained from the system. The main objective of state estimation is to provide accurate and reliable estimates of the system state, which are essential for controlling and monitoring the power system.

Phasor measurement units (PMUs) have revolutionized the state estimation process by providing high-speed synchronized measurements of voltage and current phasors at different points in the power system. PMUs provide accurate measurements of the system state, which can be used to improve the accuracy and reliability of the state estimation process.

State estimation algorithms based on PMU measurements are known as phasor state estimation (PSE) algorithms. These algorithms use synchronized phasor measurements obtained from PMUs to estimate the state variables of the power system. PSE algorithms can handle large-scale power systems and provide accurate and reliable real-time estimates of the system state.

Several studies have investigated the effectiveness of PSE algorithms based on PMU measurements. For example, the PSE algorithm was proposed based on a weighted least squares (WLS) non-linear programming model approach. It showed that the algorithm could provide accurate estimates of the system state,(Florez et al., 2021). Another study showed how a PSE algorithm based on a particle swarm optimization (PSO) algorithm and demonstrated that the algorithm could provide accurate and reliable estimates of the system state, (Kumar Sikarwar et al., n.d.).

State estimation is a critical function in power system operation and control. Accurate and reliable estimates of the system state are essential for the operation and control of the power system, including power flow control, contingency analysis, and optimal power system operation. PMUs have revolutionized the state estimation process by providing accurate and synchronized measurements of voltage and current phasors, which can be used to improve the accuracy and reliability of the state estimation process.

D. Power Quality Monitoring

Power quality monitoring is measuring and analysing the quality of electrical power in a power system. Power quality is a critical aspect of power system operation and reliability, and poor power quality can lead to equipment damage, malfunction, and even power outages. Phasor measurement units (PMUs) are widely used in power quality monitoring due to their ability to provide accurate and synchronized measurements of voltage and current phasors at different points in the power system.

PMUs provide a unique advantage in power quality monitoring over traditional power quality monitoring devices, such as power quality analysers. Conventional devices provide only limited information about the system's power quality and may not be synchronized with other devices in the system. In contrast, PMUs provide accurate and synchronized measurements of voltage and current phasors that can be used to analyser the power quality of the system in real time.

Power quality monitoring using PMUs involves measuring and analysing different power quality parameters, such as voltage sag, voltage swell, harmonic distortion, and flicker. These parameters can be analysed using advanced signal processing techniques, such as Fourier analysis, wavelet analysis, and time-frequency analysis.

An evaluation evaluated the performance of PMUs in monitoring voltage sag events in power systems and showed that PMUs could provide accurate and reliable measurements of voltage sag events,(Leborgne & Karlsson, n.d.). Another study proposed a new approach for analysing harmonic distortion using PMUs and demonstrated that the method could provide accurate and reliable harmonic distortion measurements in power systems,(Li et al., 2021).

Power quality monitoring is a critical function in power system operation and reliability. Accurate and reliable measurements of power quality parameters using PMUs can help identify and diagnose power quality problems in the power system, leading to improved power system operation and reliability.

E. Wide Area Monitoring and Control

Wide Area Monitoring and Control (WAMC) is a technology that has emerged in recent years to improve the operation, control, and security of power systems. WAMC involves the installation of a network of phasor measurement units (PMUs) throughout a power system, which can provide real-time synchronized measurements of voltage and current phasors at different points in the system. These measurements are then used to monitor the system's status, detect disturbances, and provide control actions to improve the stability and reliability of the system.

PMUs in WAMC have several advantages over traditional monitoring and control techniques. PMUs can provide high-speed, synchronized measurements of the system state, which can be used to detect disturbances in real time and provide control actions to mitigate the impact of these disturbances. PMUs can also provide accurate measurements of the system state, which can be used to improve the accuracy and reliability of system models used for power system analysis and control.

A study by Terzija,(Terzija et al., 2011). demonstrated the benefits of using PMUs in WAMC to improve the stability and reliability of power systems. The study showed that WAMC using PMUs could provide real-time monitoring and control of the system, which could enhance the stability and reliability of the system under both normal and abnormal conditions.

Another study,(Sufyan et al., 2021) proposed a framework for WAMC using PMUs, which includes the installation of a network of PMUs, developing real-time monitoring and control algorithms, and integrating these algorithms into the power system control centre. The study demonstrated the effectiveness of the proposed framework in improving the stability and reliability of power systems.
WAMC using PMUs has become an essential power system operation and control technology. WAMC can provide real-time monitoring and control of the power system, which can improve the stability and reliability of the system. PMUs can provide high-speed, synchronized measurements of the system state, which can be used to detect disturbances in real-time and provide control actions to mitigate the impact of these disturbances.

The schematic diagram of the PMU-based wide-area monitoring and control system is shown in the Figure 5 below. It plays a vital role in safe and reliable gird operation. Whenever a 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 the rest of the system.

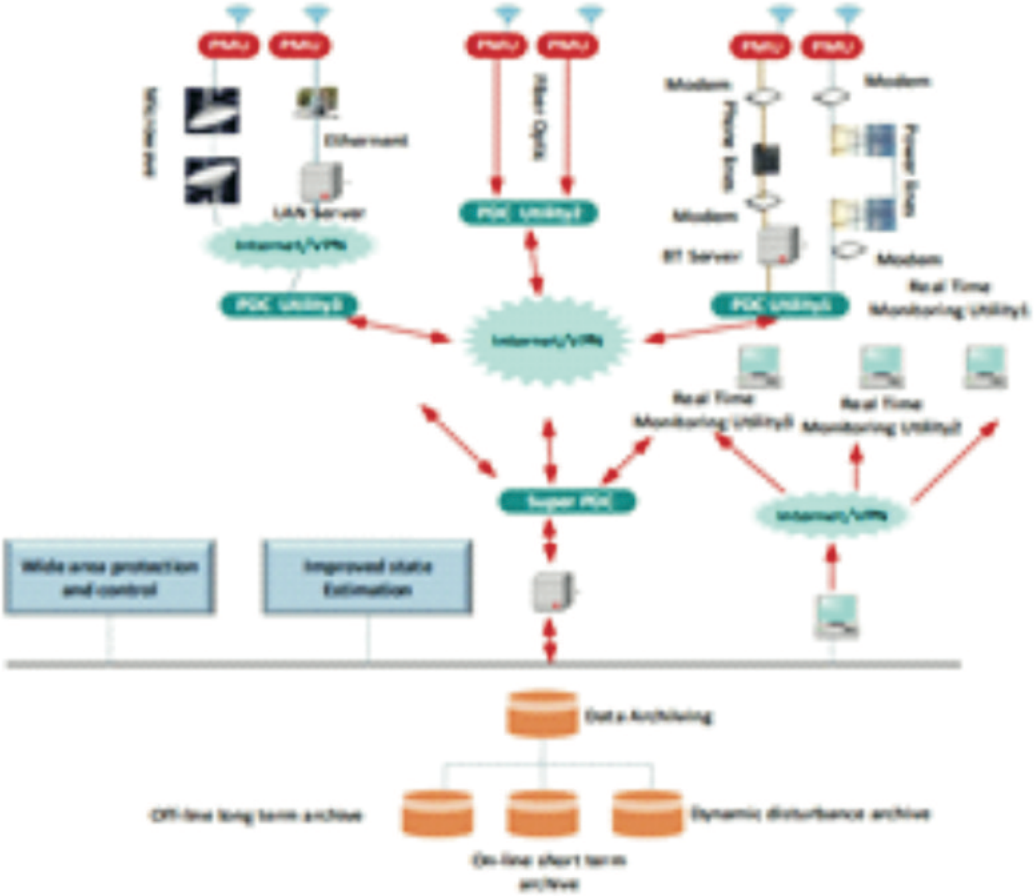

Figure 5: WAMC Architecture,(Terzija et al., 2011)

E. Voltage Stability Monitoring (VSM)

Continuously estimating the degree of power system stability is the objective of VSM. It is based on selecting important grid parameters and their respective stability index. This voltage stability index parameter comprises:

- Crucial spot voltage magnitude
- Loading margin of the power system at the operational point
- Reactive power reserves
- Modal analysis parameters include damping ratio, dominating modes, and their contribution factor to abnormal system states.

Comparing the computed stability index of the selected critical parameters to their threshold value determines their functionality. The essential components of a typical VSM system are depicted in Figure 6.

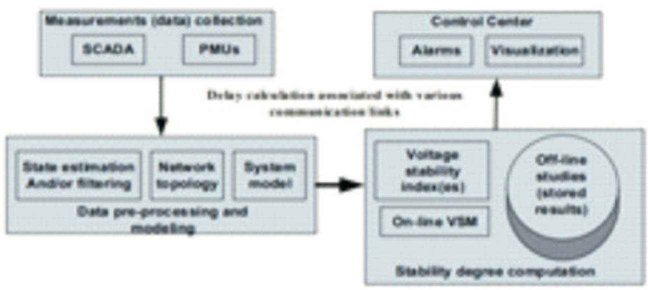

Figure 6: Essential Components of a VSM, (Kamrul et al., n.d.)

Providing reactive power assistance with flexible AC transmission system (FACT) devices is the only way to resolve the voltage stability issue. These devices are categorized as SVC, STATCOM, TCSC, and UPFC, and they can play a vital role in resolving voltage instability issues. SVC and STATCOM are the most effective of the two. Through voltage source converters, they inject or absorb VARs and provide fast help for voltage instability issues. They are also known as dynamic VAR compensation devices. STATCOM has a quicker response time than SVC, is more resistant to frequent power system changes, such as harmonic variations, and requires smaller outdoor equipment than SVC. In high voltage conditions, STATCOM acts in inductive mode and absorbs reactive power, whereas, in low voltage states, it operates in capacitive mode and injects reactive power into the system,(Li et al., 2021), (Lee & Song, 2019).

E. Renewable Energy

Renewable energy sources such as solar, wind, and hydropower are becoming increasingly important as the world seeks to reduce greenhouse gas emissions and mitigate the effects of climate change, (Abdlmnam et al., 2013). However, integrating renewable energy sources into existing power systems presents several technical and operational challenges. These challenges include variability and uncertainty of renewable energy output, limited controllability of renewable energy sources, and the need for new system planning and operation strategies to accommodate high levels of renewable energy penetration.

To address these challenges, some strategies have been developed for integrating renewable energy into power systems. Energy storage systems, such as batteries, pumped hydro, and flywheels, can store excess renewable energy and provide backup power during low renewable energy output,(Li et al., 2021). Demand-side management techniques, such as demand response and time-of-use pricing, can be used to shift electricity demand to periods of high renewable energy output. Smart grid technologies, such as advanced metering infrastructure (AMI), distribution automation, and intelligent load management, can improve power systems' flexibility and resilience in the face of renewable energy variability. Additionally, combining different renewable energy sources, such as wind, solar, and hydropower, can reduce the variability of renewable energy output and ensure a more stable power supply.

Studies have shown that careful planning and optimization of renewable energy deployment can help to minimize the impact of renewable energy variability on power system stability and reliability (Li et al., 2021). Abdlmnam,(Abdlmnam et al., 2013) investigated the impact of wind and solar power on power system stability and proposed a framework for incorporating renewable energy into power system planning and operation. The study highlighted the importance of energy storage and flexible operation strategies for ensuring the reliable integration of renewable energy into power systems.

In conclusion, integrating renewable energy into power systems is a complex process that requires careful planning and innovative solutions. However, with the use of energy storage, demand-side management, smart grid technologies, and the integration of different renewable energy sources, the reliable and stable integration of renewable energy into power systems can be achieved.

3. IMPLEMENTATION OF PHASOR MEASUREMENT UNITS (PMUs) IN POWER SYSTEMS

The implementation of PMUs in power systems involves.

A. Installation of PMUs at strategic locations

Phasor measurement units (PMUs) are installed at strategic locations in the power grid to capture the system's behaviour accurately. The placement of PMUs is essential for the complete observability of the power system, which helps to identify the sources of disturbances, monitor power flows, and measure system oscillations, which are essential for maintaining the power system's stability. The following are the different aspects of installing PMUs at strategic locations.

1. Location of PMUs: The placement of PMUs should be optimized to ensure complete observability of the power system. PMUs should be installed at critical locations, such as transmission substations, interconnections, and generator buses, to capture the system's behaviour accurately.
2. Number of PMUs: The number of PMUs required for the complete observability of the power system depends on the size of the system and the required level of observability. The minimum number of PMUs needed for the full observability of the power system is equal to the number of buses in the system.
3. Time Synchronization: PMUs must be time-synchronized to capture the system's behaviour accurately. Accurate time synchronization is critical for calculating phasors and measuring system oscillations.
4. Communication Infrastructure: PMUs generate large amounts of real-time data, which require a communication infrastructure capable of handling the data volume and providing real-time data transfer. The communication infrastructure must be secure, reliable, and capable of handling different communication protocols.

The strategic placement of PMUs helps to identify the sources of disturbances, monitor power flows, and measure system oscillations, which are essential for maintaining the power system's stability. Integrating PMUs with advanced analytics and machine learning algorithms enables the operators to perform predictive maintenance, detect anomalies, and identify potential system issues before they occur.

According to Sufyan, (Sufyan et al., 2021), the placement of PMUs should be optimized for complete power system observability. The location of PMUs should be selected based on the system's topology. They should be installed at critical locations, such as transmission substations, interconnections, and generator buses, to accurately capture the system's behaviour. The number of PMUs required for the complete observability of the power system is equal to the number of buses in the system. Accurate time synchronization is critical for calculating phasors and measuring system oscillations. The communication infrastructure must be secure, reliable, and capable of handling different communication protocols to handle the large amount of real-time data generated by PMUs.

In conclusion, the installation of PMUs at strategic sites is vital for the whole observability of the power system, which helps to identify the origins of disturbances, monitor power flows, and measure system oscillations, hence preserving the stability of the power system. The location, quantity, synchronization of time, and communication infrastructure of PMUs are crucial factors for the efficient application of PMUs in power systems.

B. Integration with supervisory control and data acquisition (SCADA) systems

Integrating phasor measurement units (PMUs) with Supervisory Control and Data Acquisition (SCADA) systems has become an important aspect of modern power systems. SCADA systems are used to monitor and control the power system in real time, and the integration of PMUs with SCADA systems can improve the situational awareness of the system and enable faster decision-making. The following are the different aspects of integrating PMUs with SCADA systems.

1. Real-time data: PMUs generate synchronized phasor measurements, which provide real-time information about the power system's behaviour. The integration of PMUs with SCADA systems enables real-time monitoring of the power system's behaviour and provides operators with accurate information about the system's status.
2. Data Quality: The quality of PMU data is critical for effective system monitoring and control. Integrating PMUs with SCADA systems helps identify and correct data quality issues in real-time.
3. Visualization: The integration of PMUs with SCADA systems enables the visualization of phasor measurements in real-time, which helps operators to understand the power system's behaviour.
4. Analytics: Integrating PMUs with advanced analytics and machine learning algorithms can help operators detect anomalies, identify potential system issues, and perform predictive maintenance.

The integration of PMUs with SCADA systems has several benefits for power system operators, including improved situational awareness, faster decision-making, and improved system reliability. Integrating PMUs with SCADA systems has become a critical technology in modern power systems. It enables power system operators to monitor and control the power system in real-time.

Integrating PMUs with SCADA systems enables the visualization of phasor measurements in real-time, which helps operators better understand the power system's behaviour. It can help identify and correct data quality issues in real time, which is essential for effective system monitoring and control. The integration of PMUs with SCADA systems also enables real-time monitoring of the power system's behaviour, which provides operators with accurate information about the system's status.

In conclusion, integrating PMUs with SCADA systems has several benefits for power system operators, including improved situational awareness, faster decision-making, and improved system reliability. The real-time data provided by PMUs, coupled with the visualization and analytics capabilities of SCADA systems, enables power system operators to monitor and control the power system in real-time, making it a critical technology in modern power systems.

C. The use of advanced analytics and machine learning algorithms

Integration of Phasor Measurement Units (PMUs) with advanced analytics and machine learning algorithms has become a significant area of research and development in power systems. PMUs provide high-speed, synchronized measurements of electrical quantities. The integration of advanced analytics and machine learning algorithms with PMUs can help provide a better understanding of the power system's behaviour, detect faults, and make predictions for system operation. The following are some aspects of integrating PMUs with advanced analytics and machine learning algorithms.

i. Fault detection: Integrating PMUs with advanced analytics and machine learning algorithms can help detect faults in the power system. Machine learning algorithms can analyse the phasor data from PMUs to identify anomalies and detect faults.

ii. Prediction of system behaviour: The integration of PMUs with machine learning algorithms can help predict the power system's behaviour. Machine learning algorithms can analyse the historical phasor data to develop predictive models for system behaviour.

iii. System optimization: The integration of PMUs with machine learning algorithms can help optimize the power system's operation. Machine learning algorithms can analyse the phasor data to identify areas of the power system that can be optimized for improved system performance.

iv. Anomaly detection: Integrating PMUs with machine learning algorithms can help identify abnormal behaviour in the power system. Machine learning algorithms can analyse the phasor data to detect deviations from normal system behaviour.

The integration of PMUs with advanced analytics and machine learning algorithms has several benefits for power system operators, including improved situational awareness, faster decision-making, and improved system reliability. By detecting faults, predicting system behaviour, optimizing system operation, and identifying anomalies, operators can take appropriate actions to improve system performance and prevent system failures.

4. CHALLENGES AND LIMITATIONS OF PMUs

Phasor Measurement Units (PMUs) are a critical component of modern power systems, providing highly accurate time-synchronized measurements of electrical quantities such as voltage, current, and frequency. These measurements are essential for monitoring the state of the power system and detecting any disturbances in real time, allowing for rapid corrective action to prevent system-wide blackouts. However, PMUs have their challenges and limitations.

A. Cost

The cost of Phasor Measurement Units (PMUs) is one of the main challenges to their widespread deployment in power systems. PMUs are expensive to install, operate, and maintain, making them costprohibitive for some utilities, especially those with limited resources. PMUs typically require specialized equipment, such as high-precision GPS receivers, communication infrastructure, and computational resources. The cost of this equipment can be significant, especially when deploying many PMUs across a wide geographic area. In addition to the equipment costs, there are costs associated with installation, testing, and ongoing maintenance.

Another factor that can drive up the cost of PMUs is the need to upgrade the existing infrastructure to support them. Many legacy power systems were not designed with PMUs in mind, so utilities may need additional investments to integrate them effectively. For example, upgrading the communication network to support high-bandwidth data transfer may require laying new fiber optic cables or installing new wireless equipment, which can be expensive.

The cost of PMUs is a challenge for smaller utilities and those in developing countries that may need more resources to invest in modernizing their power systems. In these cases, alternative solutions such as synchrophasors, which are less expensive and less accurate than PMUs, may be more appropriate.

Data Management

Data management is another significant challenge associated with Phasor Measurement Units (PMUs). PMUs generate large volumes of data in real time, which can be challenging to manage and analyse effectively. This data can include measurements of electrical quantities such as voltage, current, and frequency and other system parameters such as temperature and humidity.

To manage PMU data effectively, specialized software and computational resources are required to process and analyse the data in real time. This can be a significant challenge, especially for utilities needing more resources to invest in high-performance computing infrastructure. In addition, the large volume of data generated by PMUs can also create challenges related to data storage and archiving, which can require significant storage capacity and backup infrastructure.

PMU data management also presents challenges related to data quality and accuracy. PMU measurements are highly accurate and synchronized to a common time reference, but they can also be affected by various factors such as measurement noise, sensor errors, and communication delays. It is essential to identify and address these factors to ensure the accuracy and reliability of PMU data.

To address these challenges, ongoing research and development efforts are focused on developing new techniques for managing and analyzing PMU data more effectively. These efforts include the development of machine learning algorithms for real-time data analysis, integrating PMU data with other data sources such as weather forecasts, and using advanced data visualization tools to help operators better understand the state of the power system in real-time.

In conclusion, data management is a critical challenge associated with Phasor Measurement Units (PMUs). The large volume of data generated by PMUs and the need for specialized software and computational resources can create significant challenges for utilities. Addressing these challenges will require ongoing research and development efforts to develop new techniques and tools for managing and analysing PMU data more effectively.

Cybersecurity

Cybersecurity is a critical challenge associated with Phasor Measurement Units (PMUs). PMUs are connected to communication networks and are vulnerable to cyber-attacks, which can compromise the integrity and reliability of the power system.

One of the main challenges related to PMU cybersecurity is the complexity of the communication networks that support them. These networks are often large and interconnected, making them difficult to secure effectively. In addition, PMUs typically rely on open communication protocols such as the IEEE C37.118 standard, making them more vulnerable to cyber-attacks, (Khan et al., 2016), (Cui et al., 2022). Another challenge associated with PMU cybersecurity is ensuring the authenticity and integrity of the PMU data. Cyber-attacks can compromise the accuracy and reliability of PMU data, which can have severe consequences for power system operation and stability. Ensuring the authenticity and integrity of PMU data requires using advanced cryptographic techniques, such as digital signatures and hash functions.

To address these challenges, ongoing research and development efforts are focused on developing new techniques and tools for securing PMUs and their communication networks. These efforts include the development of secure communication protocols, integrating advanced cryptography techniques, and using intrusion detection systems to monitor communication networks for potential cyber threats.

In conclusion, cybersecurity is a significant challenge associated with Phasor Measurement Units (PMUs). The complexity of communication networks that support PMUs and the need to ensure the authenticity and integrity of PMU data requires advanced techniques and tools to secure them effectively. Addressing these challenges will require ongoing research and development efforts to develop new techniques and tools for securing PMUs and their communication networks against cyber threats.

5. CURRENT AND FUTURE RESEARCH ON SITUATIONAL AWARENESS OF POWER SYSTEMS USING PMUs

Situational Awareness of Power Systems using Phasor Measurement Units (PMUs) is an active research area in power systems engineering. PMUs are devices that can measure the electrical characteristics of a power system in real-time, such as voltage, current, and phase angle, with high accuracy and precision. The use of PMUs has enabled the development of advanced monitoring and control systems that provide real-time situational awareness of power systems, which is crucial for ensuring the power grid's reliability, stability, and security.

Current research on situational awareness of power systems using PMUs focuses on developing new techniques and algorithms for analysing the large amounts of data generated by PMUs in real-time,(Zhang et al., 2022). These techniques aim to extract useful information from the PMU data and provide actionable insights to power system operators for improved system operation and control. Some of the current research topics in this area include:

i. Big Data Analytics: With the increasing deployment of PMUs in power systems, a massive amount of data is generated in real-time. Big data analytics techniques are being developed to process and analyse this data to extract useful information for situational awareness and decision-making.

ii. Machine Learning and Artificial Intelligence: Machine learning and AI techniques are being applied to PMU data analysis to develop predictive models for system behaviour and to identify abnormal events in real time.

iii. Cybersecurity: PMUs are connected to the internet for remote data access and are vulnerable to cyber-attacks. Research is being conducted to develop cybersecurity solutions to protect PMUs and the power system from cyber threats.

iv. Visualization: Visualization techniques are being developed to present the PMU data as user-friendly and understandable to power system operators.

Future research on situational awareness of power systems using PMUs is expected to focus on the following areas:

i. Integration of PMUs with other technologies: PMUs can be integrated with other technologies such as synchrophasors, wide area monitoring systems (WAMS), and advanced analytics to enhance situational awareness and improve system operation and control.

ii. Multi-level situational awareness: The development of multi-level situational awareness techniques, which integrate data from different sources, such as PMUs, SCADA systems, and weather data, for improved decision-making in power system operation and control.

iii. Resilient control systems: Research is needed to develop resilient control systems that can operate the power system in extreme events such as cyber-attacks, natural disasters, and physical attacks.

iv. Edge Computing: Edge computing techniques can be used to process PMU data locally and reduce data transmission latency. This can be particularly useful in remote or rural areas where the network infrastructure may need to be more robust.

In conclusion, research on situational awareness of power systems using PMUs is an ongoing area of research in power systems engineering. The development of advanced analytics, machine learning, and AI techniques, along with the integration of PMUs with other technologies, will enable power system operators to make informed decisions for improved system reliability, stability, and security.

BENEFITS

Phasor Measurement Units (PMUs) provide real-time data on the state of power systems, including voltage, current, and phase angle measurements. Using PMUs to monitor the power system, operators can gain situational awareness and take proactive measures to prevent blackouts, improve reliability, and reduce costs.

Some benefits of situational awareness of power systems using PMUs include:

i. Improved Reliability: PMUs enable operators to quickly detect and diagnose power system disturbances, such as faults and outages before they cause widespread disruptions. This helps improve the reliability of the power system and reduces the likelihood of blackouts.

ii. Enhanced Grid Stability: PMUs provide real-time data on the stability of the power grid, allowing operators to take corrective action to maintain system stability. This includes adjusting generation and load balance and modifying system parameters to prevent system instabilities.

iii. Efficient Grid Operation: PMUs provide real-time data on power system conditions, which can be used to optimize the operation of the power grid. This includes optimizing generation and transmission resources, reducing energy losses, and improving efficiency.

iv. Improved Power Quality: PMUs can help identify and address power quality issues, such as voltage sags and harmonics, which can cause equipment damage and affect customer satisfaction.

v. Faster Restoration: PMUs can help speed up power system restoration by providing real-time information on system conditions and allowing operators to prioritize repairs and restoration efforts.

Situational awareness of power systems using PMUs can help improve the reliability, stability, efficiency, and overall performance of the power grid, benefiting both utilities and customers.

6. CASE STUDIES

The paper attempts to enumerate the acceptability of PMUs in wide area measurement in Africa and the rest of the World. Evidently, PMU deployment in African electricity networks is very low and the technology is gradually being accepted mainly in the pilot stages.

a. Elsewhere

Several case studies have demonstrated the effectiveness of PMUs in enhancing power system situational awareness. One such case study was conducted by the Electric Reliability Council of Texas (ERCOT) following the major blackout in 2011,(Obodoagwu, 2019). Various factors, including a heat wave, generation outages, and a transmission line trip caused the outage. The blackout affected over 3 million customers and resulted in economic losses estimated at over $7 billion.

Following the blackout, ERCOT implemented a series of enhancements to its power system monitoring and control systems, including deploying PMUs throughout its transmission system, (Obodoagwu, 2019). The PMUs provided real-time measurements of voltage and current phasors, allowing operators to detect and respond to disturbances in the system quickly. The PMUs were also used to validate dynamic models of the power system, improving the accuracy of system simulations and predictive analytics.

Another case study was conducted by the Bonneville Power Administration (BPA) following a major storm in 2015,(Machabe et al., 2020). The storm caused widespread damage to the power system, resulting in over 100 transmission lines and over 200,000 customer outages. The BPA used PMUs to monitor the system in real-time, allowing operators to quickly identify the location of outages and restore power to affected areas.

In addition, the BPA used PMUs to analyse the impact of the storm on the power system and develop predictive models of future storm events,(Machabe et al., 2020). By analysing the PMU data, the BPA could identify areas of the power system that were particularly vulnerable to storm damage and develop strategies for improving the system's resilience.

These case studies demonstrate the effectiveness of PMUs in enhancing power system situational awareness and improving system resilience. PMUs allow operators to quickly detect and respond to disturbances in the system by providing real-time measurements of voltage and current phasors. In addition, PMUs can be used to develop predictive models of power system behaviour, allowing operators to take proactive measures to prevent disruptions to the power system.

b. Africa

Little is known about the deployment of PMUs in electricity networks in sub-Saharan Africa. However, significant research work is being carried out with computer simulation of some networks like the Unified Electrical Power Network of Egypt. Another such case study was conducted by Obodoagwu,(Obodoagwu, 2019). This case study focuses on improving Nigeria's power transmission network, which connects the country with its neighbors and makes Nigeria a net exporter of electricity. The system, which has a number of voltage circuits, struggles with issues including line overloading and erratic power delivery. In order to improve real-time monitoring and overcome the shortcomings of current systems like Energy Management Systems (EMS) and Supervisory Control and Data Acquisition (SCADA), the study introduces Phasor Measurement Units (PMUs). PMUs outperformed SCADA systems in a thorough investigation of the 330 kV transmission lines in southwest Nigeria, demonstrating their efficiency in precisely detecting single-line faults quickly. Even with limited observability, PMUs showed promise for cutting-edge outage detection software.

Another case study is in South Africa's power system (Eskom), Phasor Measurement Units (PMUs) have been deployed to monitor small signal disturbances and predict instabilities within the network. A 2014 study identified a 0.3 Hz interarea oscillatory mode between the predominantly hydro-powered North and the mainly thermal-powered South of the Southern African Power Pool (SAPP). This mode is triggered by system disturbances in SAPP and Eskom, particularly during the evening when hydro units increase their capacity to meet peak demand. To maintain system security, a Special Protection Scheme activates when power swings on the Eskom-Zimbabwe Electricity Supply Authority (ZESA) AC tie-line exceed set limits, effectively separating the North and South systems(Machabe et al., 2020).

In September 2018, another power system event was detected by Eskom's Wide Area Monitoring System (WAMS), resulting in a low-frequency incident with oscillating active power for approximately 4 minutes. This event posed a significant risk to the power system and the possibility of a blackout. The case highlights the importance of predicting such incidents for power system security and situational awareness, a task significantly improved with the availability of PMU data,(Machabe et al., 2020).
As enumerated earlier, WAMS rely on effective communications backbone to function properly. Most of the electricity networks in Africa struggle with such provisions, especially the Nigerian Transmission networks. This could be the main reason for the low implementation and deployment of PMUs. A World

Bank study revealed that as far back as 2016 there were about 3,448 dormant PMUs installed in the African electricity networks,(Nangia et al., 2016) . This is shown in Table 1 below.

Table 1: List of Countries with Installed Dormant PMUs, (Nangia et al., 2016).

COUNTRY	DORMANT PMUS	COUNTRY	DORMANT PMUS
Botswana	61	Namibia	253
Congo, Dem. Rep.	22	Niger	1
Côte d'Ivoire	2	Nigeria	251
Djibouti	2	South Africa	2,308
Equatorial Guinea	8	Swaziland	80
Ghana	170	Tanzania	3
Kenya	64	Uganda	19
Mauritius	33	Zambia	20
Mozambique	31	Zimbabwe	18
Total			3,448

In fact, the implementation of Phasor Measurement Units (PMUs) in these African power transmission systems will led to significant improvements in system monitoring, situational awareness, and overall stability. In Nigeria, this development addresses the current issues in the electricity sector and strengthens the country's electrical infrastructure.

Similarly, in South Africa, the deployment of PMUs within Eskom's power system has enhanced system monitoring and stability. The discovery of a complex inter-area oscillatory mode between hydro and thermal regions in the Southern African Power Pool (SAPP) underscoring the importance of PMUs. These devices also play crucial role in predicting and mitigating critical incidents, such as the active power oscillation in September 2018, thereby bolstering power system security and situational awareness.

Overall, the integration of PMUs will is vital in overcoming challenges and reducing risks, ultimately contributing to more reliable and resilient electrical grids. These case studies emphasize the significance of advanced monitoring technologies in safeguarding modern power systems.

CONCLUSION

In conclusion, Phasor Measurement Units (PMUs) are important technology for enhancing situational awareness (SA) and improving power system stability and efficiency. The high-speed and synchronized measurements of voltage and current phasors provided by PMUs enable real-time monitoring and control of power systems. PMUs have numerous benefits, such as improved reliability, enhanced security, better power quality, and increased efficiency. They play crucial role in power system stability analysis and effective in improving the accuracy and reliability of stability analysis. With the increasing deployment of PMUs in power systems worldwide, the field of power system monitoring and control is rapidly evolving, leading to new insights into the behavior of power systems and enabling more effective and efficient operation of these critical networks.

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