

# **A Hybrid PMU-PDC-Cloud IoT Architecture for Enhanced Power Grid Monitoring**

Ahmed S Rahi\*, Hassan Jassim Motlak, Riyadh Toman Thahab

Department of Electrical Engineering, University of Babylon, Babylon, Iraq

Received 02 July 2025; received in revised form 01 December 2025; accepted 03 December 2025

DOI: <https://doi.org/10.46604/peti.2026.15356>

## **Abstract**

Monitoring power grids is critical to maintaining their reliability and stability, especially with the increasing integration of distributed energy resources (DERs). This study aims to develop a smart and scalable power grid monitoring system. The proposed system integrates phasor measurement units (PMUs), a phasor data concentrator (PDC), and a cloud-based Internet of Things (IoT) platform to achieve continuous monitoring and analysis. The system enables simultaneous measurements, real-time visualization, and predictive analytics using advanced frequent tracking algorithms. The cloud infrastructure enables real-time data visualization. Experimental evaluation demonstrates that the system achieves high sensitivity in fault detection, accurately identifying voltage variations as small as 0.01 pu based on system nominal voltage, phase angle deviations within  $\pm 5^\circ$ , and frequency anomalies. This enhances proactive fault detection and reduces service interruptions.

**Keywords:** power grid monitoring, phasor measurement units, phasor data concentrators, cloud computing, fault detection

## **1. Introduction**

The electrical grid monitoring system plays a critical role in managing the increasing complexity of modern power networks [1-2]. This complexity arises from the continuous expansion and integration of renewable energy sources, such as solar photovoltaic panels and wind turbines, which demand enhanced situational awareness and real-time analytics [3-4]. However, implementing fully integrated monitoring systems remains a challenge [5-6].

Advanced technologies such as PMUs have been introduced in response to these challenges [6]. These devices provide synchronized, high-resolution measurements of voltage, current, phase angle, and frequency from multiple grid points, based on a common GPS time standard [7-8]. With sampling rates of up to 120 measurements per second compared to traditional SCADA systems' update intervals of 2–4 seconds, PMUs enable a much more accurate representation of the grid's dynamic behavior [9].

PMUs are connected via a network with PDCs to form a local monitoring system that divides the system into specific areas for monitoring and maintenance [10]. PDCs are deployed to aggregate and analyze these data streams, providing comprehensive wide-area situational awareness through systems known as Wide Area Measurement Systems (WAMS) [9, 11].

These tools are pivotal in predicting network conditions and detecting faults. Cloud-based monitoring solutions have also emerged to facilitate remote access to power systems in vast or hard-to-reach areas. Platforms like ThingSpeak, AWS IoT Core, and Google Cloud IoT enable real-time visualization, control, and performance optimization, reducing operational costs and supporting proactive maintenance strategies [12-13].

---

\* Corresponding author. E-mail address: [eng799.ahmed.suadia@student.uobabylon.edu.iq](mailto:eng799.ahmed.suadia@student.uobabylon.edu.iq)

This paper proposes a smart power grid monitoring system that combines phasor measurement units (PMUs), phasor data concentrators (PDCs), and a cloud-based IoT platform to overcome the limitations associated with traditional monitoring architectures. The system contributes to the following:

- (1) Provide capabilities that support real-time fault detection, prediction accuracy, and operational insights by utilizing synchronous phasor data and advanced cloud-based analytics.
- (2) Provide capabilities that support future network planning and forecasting.
- (3) Improve sensitivity by defining threshold values for voltage, phase angle, and frequency, which indicate the severity of network disturbances.
- (4) Accurate measurements are collected at each bus via distributed measurement units.
- (5) Enables analysis of fault propagation across different network segments, especially those showing deviations in voltage, frequency, or phase angle.

The proposed approach was applied to an IEEE 14 bus test system, and simulation results demonstrated the proposed system's ability to detect faults with high accuracy and good sensitivity to network dynamics. The remainder of the paper is organized as follows: Section 2 describes the proposed system, Section 3 presents the methodology and proposed system, Section 4 describes PMUs: simulation and coding, Section 5 presents results and discussions, and Section 6 concludes the paper.

## **2. Related Work**

Rahman et al. [14] presented a study on the use of PMUs within wide area monitoring systems (WAMS) for intelligent fault detection in electrical grids. The researchers combined real-time grid data and machine learning algorithms to design a system that rapidly identifies and analyzes fault patterns. The results showed that combining PMU data with intelligent models improved the accuracy of time-based diagnosis and the operational response speed of the grid. However, deep learning algorithms entail high computational complexity. Additionally, the need for massive amounts of data limits their practical application in wide-area networks. While this research provides a strong reference on the use of PMUs with artificial intelligence, it does not cover the integration of the PDC and cloud connectivity.

Benavides et al. [15] presented an integrated study of energy management in remote microgrids based on the Internet of Things (IoT) and the ThingSpeak platform to enable real-time monitoring. The study focused on real-time data from measurement systems to apply linear regression and machine learning algorithms to improve PV plant productivity and operational efficiency. The results demonstrated high monitoring efficiency. However, the system faced technological limitations related to the limited data processing speed in the IoT layer and the lack of a real-time synchronization mechanism compared to what is provided by PMUs. Furthermore, the lack of a local PDC for local monitoring and analysis limited its performance.

Arenas Ramos et al. [16] presented a study aimed at developing an open-source software platform to integrate various energy system monitoring devices, including power quality monitoring devices (PQMs). These include PMUs and smart meters (SMs), with artificial intelligence (AI) technologies to increase network monitoring capacity. The results demonstrated high accuracy and reliability in data processing. However, implementation is challenging due to technical complexity, high implementation costs, and the need for large amounts of data. Furthermore, the study did not discuss the use of cloud monitoring and the PDC algorithm for monitoring.

Wright and Wolthussen [17] indicated that the resilience of power grid condition estimation systems was enhanced by the application of a PDC-specific retransmission algorithm. This algorithm aimed to address data loss or delay issues. It provided a dynamic timing approach for retransmitting lost or delayed data, filling in the links in the PMU data, and improving the quality of the estimations. The results demonstrated good accuracy. However, the study did not address the integration of the PDC with the IoT for monitoring.

Morato et al. [18] presented a study that simulated PMU failures to assess the monitoring system's ability to respond in real time and analyze sudden changes in phasor data. The researchers used a dynamic simulation environment that allowed them to introduce temporary faults in phasor signals and observe how the system reacted to these temporal and angular deviations. The results demonstrated the PMU's ability to detect changes at high speed. However, the study did not incorporate an advanced analysis layer, such as a PDC or synchronous cloud monitoring mechanisms, for monitoring the electrical grid.

Soufiane et al. [19] conducted a study aimed at improving large-scale smart grid monitoring using PMU and PDC. This study aimed to increase the accuracy of determining operating conditions, particularly in the context of the proliferation of solar power plants. To achieve this, the Alternating Directional Method of Multiplier (ADMM) algorithm was implemented to perform data analysis across different regions and improve synchronization between local and central PDC. The results showed that increasing the number of PMUs improves the accuracy of the analysis. However, the study did not discuss the integration of the PDC with cloud monitoring.

Zahidul Islam et al. [20] presented a network monitoring study based on synchronous PMUs. The study focused on developing a routing algorithm that ensures PMU data transmission to PDC even when communication links fail. The results showed a slight improvement in delay reduction and monitoring reliability compared to traditional methods. However, the system faced limitations related to direct integration with the IoT layer. Furthermore, performance was limited by data analysis at the PDC level only, without incorporating advanced real-time cloud control. Also, the study did not employ on a hybrid PDC-Cloud architecture, which limits its ability to support integrated monitoring and analysis.

The study by Castillo et al. [21] focused on analyzing the statistical behavior of PMU errors to improve monitoring accuracy in large-scale power systems. The researchers used an experimental analytical approach based on real laboratory data to measure the impact of noise and time skew. The results showed that errors occur with varying probabilities under different operating conditions, providing a deeper understanding of the nature of PMU errors. The primary contribution is providing a precise statistical description. However, the study did not discuss the design of the PDC unit, nor did it utilize its integration with cloud monitoring.

Table 1 Comparison between Related Works and Proposed System

Aspect	Related Works	Proposed System
Contribute	Focused on PMUs, AI, or IoT separately to enhance monitoring and fault detection [16, 19].	Integrates PMUs, PDCs, and IoT-cloud to achieve unified, real-time smart monitoring.
Architecture	Mostly single-layer (PMU-PDC or PMU-Cloud) with limited synchronization [20].	Multi-layer hybrid (PMU-PDC-Cloud) enabling synchronized and real-time analytics.
Method	Used AI models, ADMM, retransmission, or open-source platforms for data analysis [14, 16, 19-20].	Employs PMU data for monitoring and analysis during PDC, in addition to integrating it with cloud monitoring, and has been tested on an IEEE 14-bus system.
Strength	Improved data accuracy and fault detection using advanced algorithms [16, 18, 21].	High sensitivity to voltage, angle, and frequency changes; tracks fault propagation.
Limitation	High computational load, weak integration, and limited real-time capability [20-21].	Reduces complexity, enhances synchronization, and improves real-time performance.

Table 1 illustrates the main differences between previous studies and the proposed system, demonstrating that the research has overcome technical limitations in integration and real-time synchronization. The table also confirms the effectiveness of the new design by integrating PMUs and PDCs with the cloud platform to achieve integrated and accurate smart monitoring of the grid.

### 3. Methodology and Proposed System

Advanced monitoring ensures grid continuity and mitigates sudden and future outages caused by varying load fluctuations and increased demand for electrical power, which can impact the grid in the future. Consequently, there is a need for real-time, high-precision measurement of the entire grid, ensuring accurate readings and detecting even subtle changes in voltage and current. For this reason, the PMUs are the ideal solution. After receiving PMU signals from all buses in the grid, an algorithm was developed, represented by the PDC unit, which performs comprehensive and systematic data analysis. This includes fault detection, precise location, and the ability to track subtle changes that indicate a sustained increase in load or sudden fluctuations in voltage and angle. Fluctuations observed in the FFT signal also provide clues to specific disturbances, such as future outages. The FFT algorithm, integrated into the PDC unit, analyzes all voltage, current, phase angle, and network frequency signals from the PMU under various operating conditions. The data is also transmitted via the cloud for remote monitoring in remote areas. The monitoring philosophy is not limited to detecting faults only, but also the dynamic change in loads that expose the grid to outages and damage to some parts, which in turn causes increased maintenance costs and economic impacts.

In this work, the synchrophasor measurements are created and time-stamped in accordance with the IEEE C37.118.1 standard. The nominal system frequency is 60 Hz, and each PMU samples the analog signals at a rate of  $F_s = N_{sr} \times 60$  samples per second, where  $N_{sr}$  is the number of points per cycle (e.g., 128 points/cycle  $\rightarrow$  7680 samples/s). The phasor reporting rate is then selected from the frame rates allowed by the standard for 60 Hz systems (10, 12, 15, 20, 30, or 60 fps). All PMUs are synchronized to a common GPS standard, and time stamps are appended according to IEEE C37.118.2 [21] for real-time data communication. This ensures uniformity in phase angle reporting, frequency-deviation tracking, and rate-of-change-of-frequency (ROCOF) across the network, while maintaining interoperability with installed PDCs and cloud-based monitoring systems.

The analysis mechanism in the PDC module algorithm relies on mathematical equations that process signals transmitted from PMUs. Equations for calculating instantaneous power, voltage variations, phase angle, and frequency are used to derive the actual behavior of the electrical grid system. The Fast Fourier Transform (FFT) equation is applied to analyze the frequency components and detect any abnormal deviations that may indicate disturbances or the onset of faults. The module also performs a continuous comparison between measured values and established baselines for voltage, phase angle, and frequency to determine stability. Furthermore, the time variation of these values is analyzed to estimate system dynamics and detect subtle deviations that may not be apparent in instantaneous measurements. In this way, the PDC module provides an integrated system for high-precision monitoring and rapid response within modern networks, as described in the mathematical model outlined in Eq. (1) [22].

$$\Delta V = \frac{\Delta V}{\Delta t}, \Delta \delta = \frac{\Delta \delta}{\Delta t}, \Delta f = \frac{\Delta f}{\Delta t} \quad (1)$$

where  $\Delta V$  denotes the rate of change of voltage,  $\Delta \delta$  denotes the rate of change of phase angle, and  $\Delta f$  denotes the rate of change of frequency. These derivatives are essential indicators for detecting sudden changes that indicate instability or faults in the electrical network. Fast Fourier Transform (FFT) for frequency analysis is given by Eq. (2) [23].

$$f(x) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi n/N} \quad (2)$$

where  $f(x)$  is the Fourier transform of the discrete signal  $x(n)$  and  $N$  is the total number of sample points. This formula allows spectral analysis to identify harmonic distortions and frequency deviations that may affect network stability.

$$\begin{cases} \Delta V > V_{th} \\ \Delta \delta > \delta_{th} \\ \Delta f > f_{th} \end{cases} \quad \text{a fault condition} \quad (3)$$

where  $V_{th} = 0.01 \text{ pu}$  is the minimum allowable voltage variation,  $\delta_{th} = 5^\circ$  is the minimum allowable phase angle deviation, and  $f_{th} = 0.5 \text{ Hz}$  is the minimum allowable frequency variation. Exceeding any of these limits indicates a fault that requires preventive action.

Steady-state response (SSR) is an analytical tool used in electrical network analysis to determine the steady-state stability of voltage or current. It is therefore suitable for measurement and monitoring applications to determine performance efficiency over a period of time. It is the basis for engineering decisions, such as determining the effectiveness of fault detection algorithms. It also has the potential to provide a simplified and accurate means of determining long-term system behavior. The SSR model derived in [4] was adopted as a key analytical tool for capturing minute changes in signals and interpreting system dynamics under various operating conditions for accurate fault diagnosis [23].

$$SSR = \frac{1}{N} \sum_{i=1}^N x_i \quad (4)$$

where SSR is the steady-state response,  $x_i$  is the measured value at monitoring point  $i$ , and  $N$  is the total number of measurements. This averaging process provides a reliable representation of the network's stability behavior, focusing on monitoring long-term stability under operating conditions.

The Importance of the Steady-State Response (SSR) Function in a PDC Monitoring Unit:

- (1) It continuously tracks the phase angle and displays changes in the expected state of instability, while accurately identifying the moment of fault initiation by detecting deviations.
- (2) It provides diagnostic data that can be collected for later use in diagnosing the nature and causes of the fault.

The Steady-State Response (SSR) function in network monitoring can be summarized as follows:

- (1) It enables the monitor to determine when the system deviates from its stable operating state.
- (2) It detects disturbances early, helping the operator with maintenance and saving costs.
- (3) It provides valuable and important information for improving the system and control algorithms.
- (4) It compares the expected and actual system response during changes and disturbances.
- (5) It enhances the ability of network operators and monitors to make quick decisions. The modern use of PMU technology provides all this flexibility in monitoring and operating the electrical network, along with the use of several distinct monitoring methods that increase network efficiency.

Fig. 1 illustrates the overall layout of a monitoring system based on concurrent measurements. The process begins by measuring electrical variables at various points in the IEEE-14 Bus network using PMUs. These measurements are transmitted simultaneously to the PDC, which integrates the incoming signals and executes a series of analytical algorithms, such as variation detection, Fourier transform, and fault analysis. The figure also shows how each analytical function within the PDC is linked to its reference mathematical equations, enhancing the accuracy of evaluating the system's dynamic behavior. After

processing is complete, the results are sent to a cloud-based monitoring platform, which provides an additional layer to the system. The figure thus provides a comprehensive overview of the data flow and the roles of the key components in the proposed monitoring system.

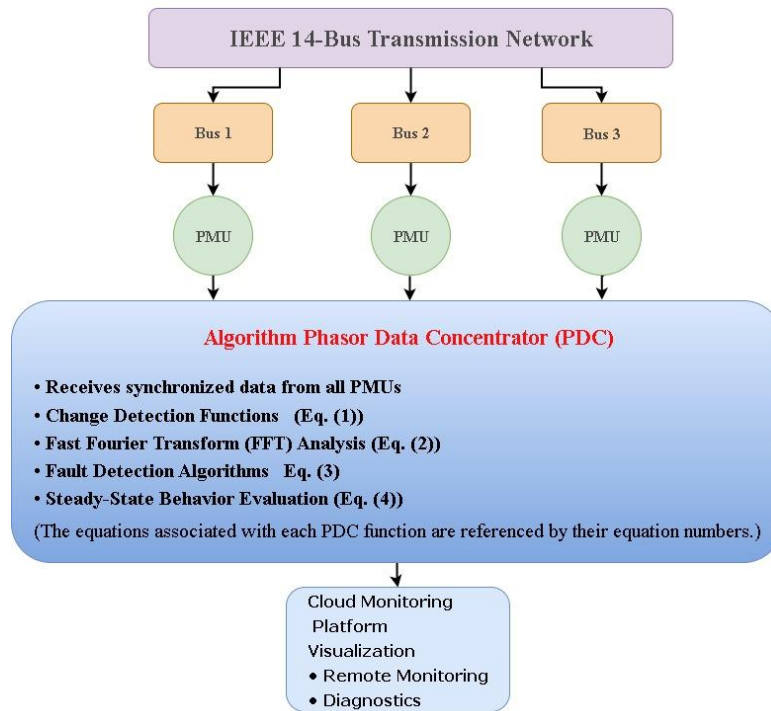


Fig. 1 Block diagram of the proposed monitoring system

#### 4. Phasor Measurement Unit: Simulation and Coding

In this work, the PMU is considered the ideal solution for monitoring electrical networks, as it features the following:

- (1) Supports rapid event detection (faults, oscillations, islanding) because PMUs provide sequential frames at a high rate (e.g., 30-120 measurements/second) compared to traditional SCADA (e.g., every few seconds or minutes) [9].
- (2) Improved state estimation: the introduction of simultaneous measurements reduces uncertainty in network status estimation and accurately monitors voltage drop, phase angle shift, and power flows.
- (3) Supports predictive analytics: Accurate time series enable algorithms to detect changes or gradual deterioration in stability, generating early warnings.

In this section, the system applied in the simulation is explained. The proposed system was implemented in the MATLAB/Simulink environment to monitor the IEEE 14 transmission system with modifications, including a fault block that simulates a three-phase fault at the line separating buses 1 and 2 [24]. Also, voltage measuring units were installed on each bus, and the voltage at each bus was measured on the grid. The grid is characterized by a voltage value of 230 kV, with essential components including generators, capacitors, and load requirements. The PMU units were connected to a PDC unit to analyze data, monitor network behavior, and identify faults.

Fig. 2 shows the test setup for evaluating the effectiveness of the PDC-based analysis system. It also illustrates the data processing mechanism transmitted from three synchronous PMUs. The PMUs begin by measuring variables, specifically voltage, phase angle, and frequency, and tracking their temporal variations. These values are compared to pre-defined reference thresholds to detect abnormal conditions such as sudden voltage drops or frequency deviations. The Fast Fourier Transform (FFT) then analyzes the frequency components with high accuracy, enabling the identification of any oscillations or abnormal

frequencies that may reflect disturbances in the electrical system. The Steady-State Response (SSR) is then calculated to monitor the network dynamics. The final result is the detection of transient effects for emergency and other conditions, providing integrated monitoring that protects the network and ensures system stability and operational efficiency.

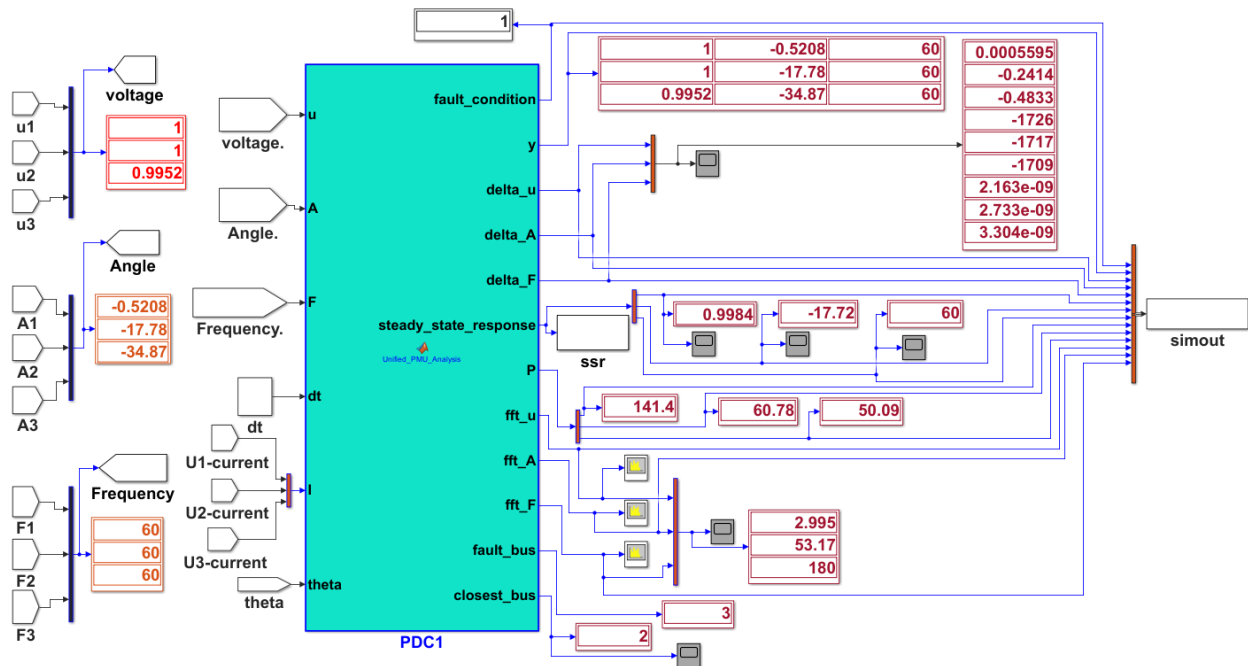


Fig. 2 Phasor data concentrate (PDC) data analysis simulation using an integrated processing

The PDC algorithm for monitoring the electrical grid analyzes data received from PMUs to evaluate the electrical grid's performance based on voltage, phase angle, and frequency. This algorithm combines data from three PMUs, detects temporal variations, and detects faults. It uses a frequency domain analysis using a fast Fourier transform (FFT). The algorithm also checks for threshold violations by comparing threshold values with the values received from the grid in successive phase synchronization frames. The accepted thresholds are  $\Delta V = 0.01 \text{ pu}$ ,  $\Delta \delta = 5^\circ$ , and  $\Delta f = 0.5 \text{ Hz}$ . These limits follow the C37.118.1 convention [2], which specifies the inter-frame variation limits for voltage, phase angle, and frequency.

The algorithm used in PDC is illustrated below:

Input:  $V(t)$ : Voltage phasor samples,  $\delta(t)$ : Phase angle samples,  $f(t)$ : frequency samples,  $dt$ : Sampling time interval

Output: SSR ( $V$ ,  $\delta$ ,  $f$ ): Steady-State Response values, FFT ( $V$ ,  $\delta$ ,  $f$ ): frequency-domain analysis results, Flag: Fault detection status

Begin

1. Compute Time-Based Changes (Derivatives)

$\text{delta\_V} \leftarrow [0; \text{diff}(V) / dt]$  Voltage rate of change

$\text{delta\_}\delta \leftarrow [0; \text{diff}(\delta) / dt]$  Phase angle rate of change

$\text{delta\_f} \leftarrow [0; \text{diff}(F) / dt]$  Frequency rate of change

2. Set Detection Thresholds

$\text{Threshold\_V} \leftarrow 0.01$  Voltage variation threshold (p.u),  $\text{Threshold} \leftarrow 5^\circ$  phase angle variation threshold (deg)

$\text{Threshold\_F} \leftarrow 0.5$  frequency variation threshold (Hz)

3. Fault Detection Logic

If ( $\text{delta\_V} > \text{Threshold\_V}$ ) OR

( $\text{delta\_}\delta > \text{Threshold\_}\delta$ ) OR

( $\text{delta\_f} > \text{Threshold\_f}$ ) Then

Flag  $\leftarrow$  "FAULT DETECTED"

```

Else
Flag ← "NORMAL OPERATION"
End If
4. Compute Steady-State Response (SSR)
SSR_V ← mean(V), SSR_δ ← mean(δ), SSR_f ← mean(f)
5. Perform frequency Spectrum Analysis (FFT)
N ← length(V)
V, δ, F ← column vectors
fft_V_full ← abs (FFT (V, N))
fft_δ_full ← abs (FFT (δ, N))
fft_F_full ← abs (FFT (F, N))
fft_V ← fft_V_full [1 : floor (N / 2)]
fft_δ ← fft_δ_full[1 : floor (N / 2)]
fft_f ← fft_F_full[1 : floor (N / 2)]
Note: The symbol (full) indicates that the variable contains the full frequency spectrum resulting from the FFT process (positive and negative frequency components) before the positive half is determined for analysis.
6. Output Results
Output {SSR_V, SSR_δ, SSR_f, fft_V, fft_δ, fft_f, Flag}
End Algorithm

```

The above algorithm monitors the voltage deviation with high sensitivity, which makes it ideal for grids with high penetration of distributed energy sources. When voltage fluctuations occur at the common connection points (PCC) between DG units and the grid, the proposed system using synchronous PMUs can detect these changes immediately and send them to the cloud for analysis and prediction of a potential outage or fault. Instantaneous changes indicate the entry or exit of sudden loads, or frequent changes indicate problems at the power generation station. Similarly, extreme changes such as a sharp drop or sharp rise in voltage indicate a fault in that area.

Renewable energy sources are deployed in microgrids to fill power shortages in areas with weak supply. Monitoring these grid segments is essential to monitor stability and improve performance through changes in supply, including changes in the source's supply, as it is unstable and dependent on fluctuations in radiation, in addition to the possibility of faults. Synchronous data from PMUs can be used to coordinate the operation of inverters connecting renewable energy sources, reducing reverse power flow and improving the dynamic stability of the system.

The PDC is the network data analyzer. It collects PMU data and processes it through algorithms to form a unified time reference for analysis. It also monitors data quality through internal functions, ensuring reliable cloud analytics. The hierarchical (local/central) structure enables local filtering, compression, and real-time event detection, reducing network load and improving responsiveness. Finally, cloud integration enables the transmission of structured time packets for analysis, forecasting, and reliable storage. That cloud integration makes a pool of data available to every agent in the grid.

Integration with IoT Cloud platforms enables a second layer of monitoring and future data storage for analysis and planning, as well as real-time visualization and reliable predictive analytics through a PMU/PDC architecture. Although there is a slight delay, the adoption of edge processing and parallel ingestion technologies minimizes the impact and keeps operational concurrency within operational limits. A voltage accuracy of 0.01pu based on system nominal voltage and a phase angle deviation of  $\pm 5^\circ$  enables high sensitivity, allowing early detection of subtle operational deviations, enhancing grid reliability and resilience.

## 5. Results and Discussions

The proposed PMU-PDC cloud-integrated monitoring system was simulated with an IEEE 14 bus system in the Simulink environment. Fig. 3 displays the network voltage signals transmitted by the PMU in a stable, fault-free state. Connecting PMUs to a bus provides a detailed visualization of the network to detect any signal changes, which helps detect faults and analyze the impact of the fault on other network components. This is illustrated in Fig. 4 when a fault occurs, providing a clear comparison between the two cases and highlighting the importance of installing PMUs on each bus.

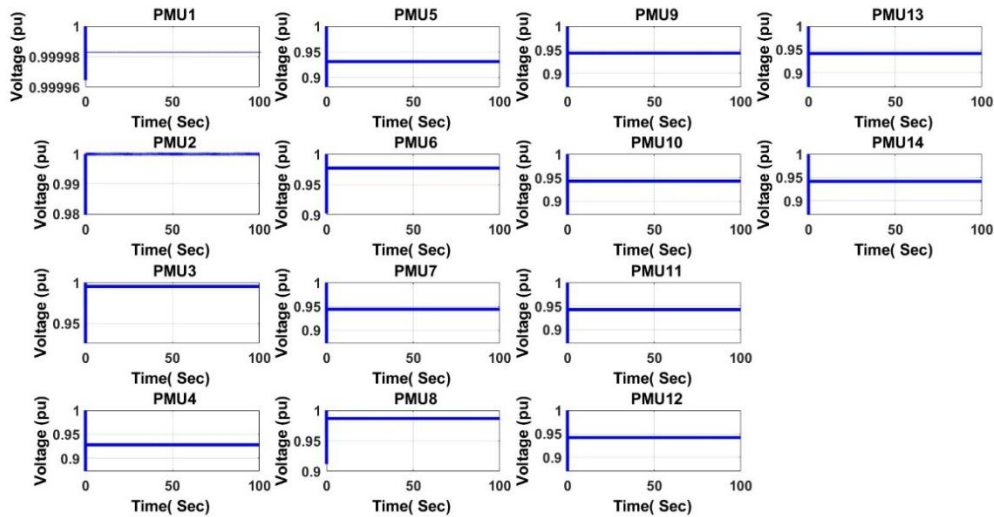


Fig. 3 Voltage signals received from all PMUs in the 14-bus network at a Stable system (no fault)

Fig. 4 illustrates the results of a fault occurring in the network and the extent of the fault's impact on each conductor based on its proximity to the fault location and the conflicting impedances in the transmission lines. The results also record the time of fault occurrence, which ranges from 30 to 40 seconds after the test, indicating the gradual impact of the fault based on the distance between the fault location and the point measured by the PMU. The results demonstrate accurate synchronization of data transmission to the monitoring site, reinforcing the importance of the PMU in fault detection and network data analysis.

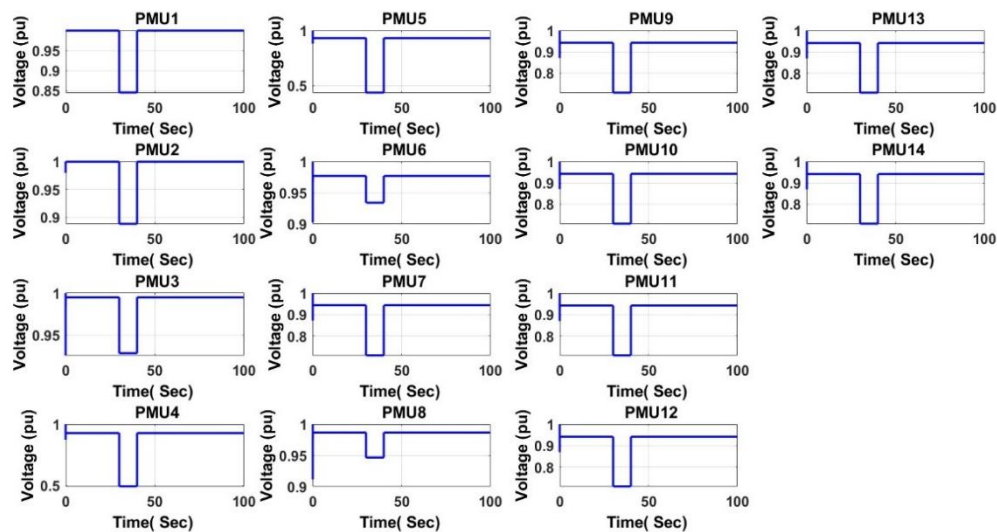


Fig. 4 Voltage signals received from all PMUs in the 14-bus network for a fault occurrence at buses 1, 2, and 3

Fig. 5 shows the phase angle measurement signals for each bus in the network coming from the PMUs. The results clearly show stability and no abnormalities or faults, indicating no deviation in the phase angle measurement. Fig. 5 is important in its comparison with Fig. 6, which shows the phase angle status during a fault.

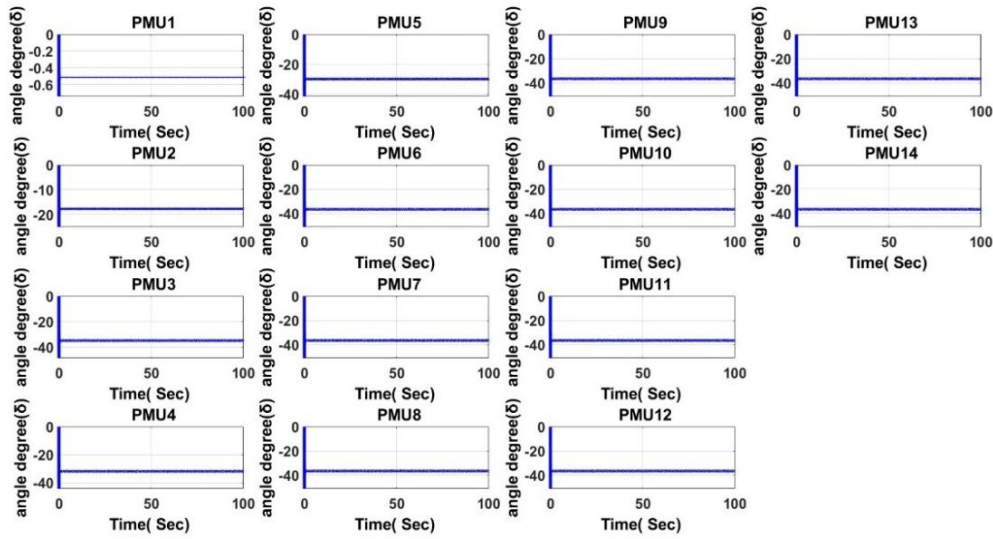


Fig. 5 Phase angle signals received from all PMUs in the 14-bus network at a Stable system (no fault)

In Fig. 6, the signals show a phase angle deviation fault within a specific time period of 30 to 40 seconds of the test. This situation provides several explanations, including the importance of PMUs for real-time monitoring, which provides a head start in making decisions to avoid danger. The phase angle indicates the effect of the fault propagation on the rest of the network over time and the gradual impact.

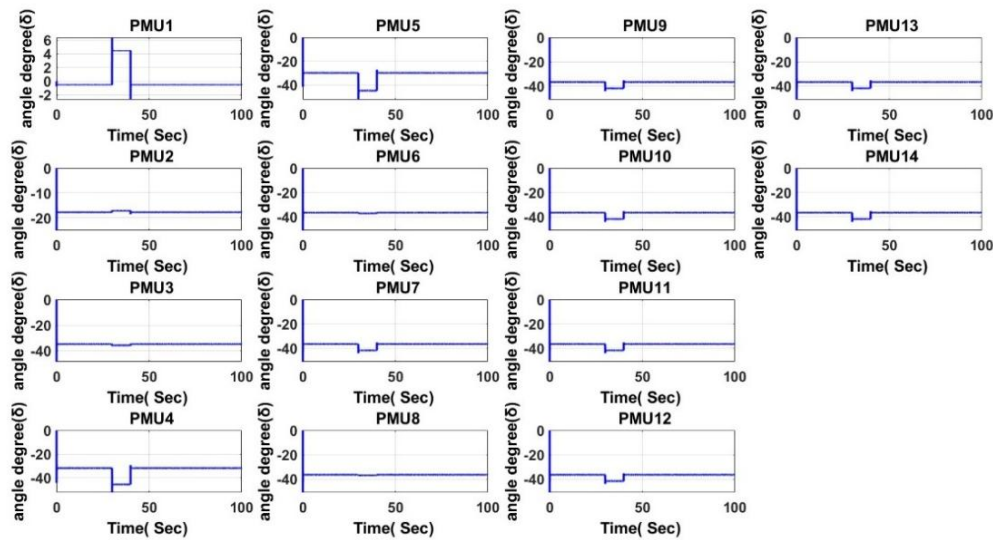


Fig. 6 Phase angle signals received from all PMUs in the 14-bus network at the fault

Fig. 7 shows the frequency signals for 14 buses arriving from the PMUs during a sudden failure. Large frequency changes are detected during a certain period of network disturbance. The sudden frequency change reflects the disruption for a period of time, after which the network returns to a stable state. The observed changes are not simply changes in value; they represent a deterioration in the instantaneous frequency stability, which is one of the most critical indicators of electrical grid operation. The PMUs have proven to efficiently monitor these changes in real time, providing time-stamped data synchronized with GPS.

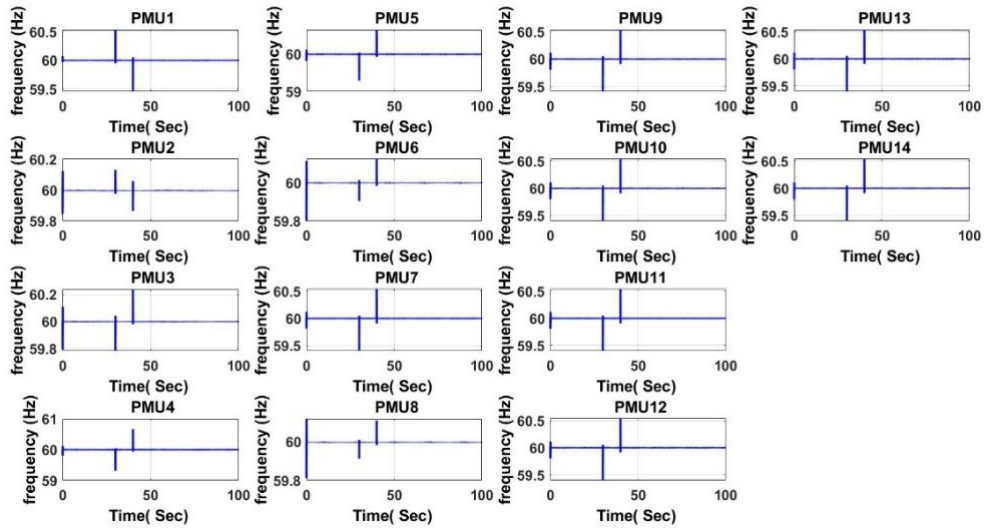


Fig. 7 Frequency signal received from all PMUs installed on network buses during a fault condition

Fig. 8 shows an analysis of the Steady State Response (SSR) function, which is part of the PDC algorithm that monitors the network and analyzes data based on signals coming from the PMUs. It specifically shows the Steady State Response (SSR) results for voltage, angle, and frequency in a stable system without any faults for comparison. Fig. 9 shows the fault condition to demonstrate the role and importance of the function. The importance of the SSR lies in studying the long-term stability of the network, and the data can be stored for future study and planning through the information provided by the SSR.

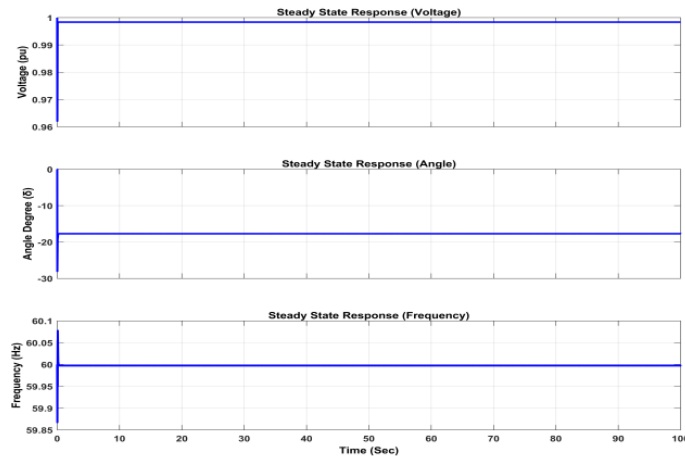


Fig. 8 SSR signals of the electric network under normal operating state (no fault)

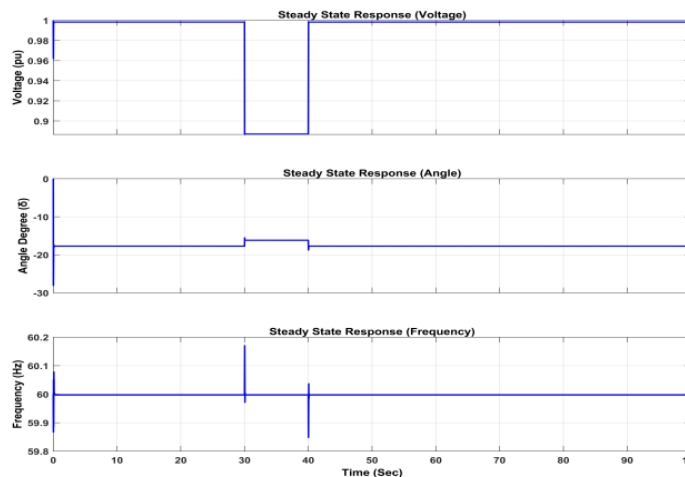


Fig. 9 SSR signals of the electric network under fault conditions (at fault)

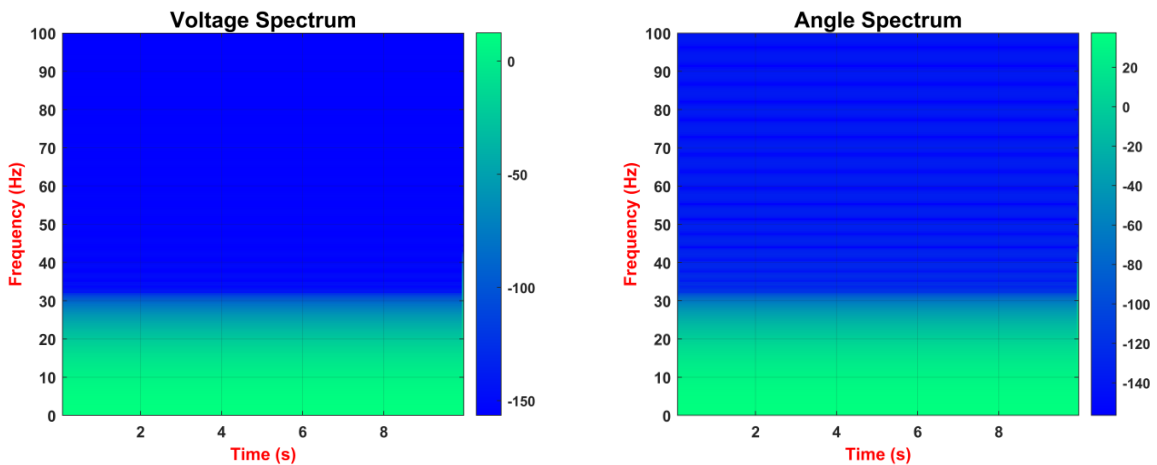
Fig. 9 shows the results of the SSR function, which depicts the sudden changes in the phase angle in the network. The function proves effective in tracking rapid changes in phase angle during a fault, which implies the SSR code within the PDC module has proven effectiveness in monitoring the network from a different perspective.

### 5.1. Fault Analysis

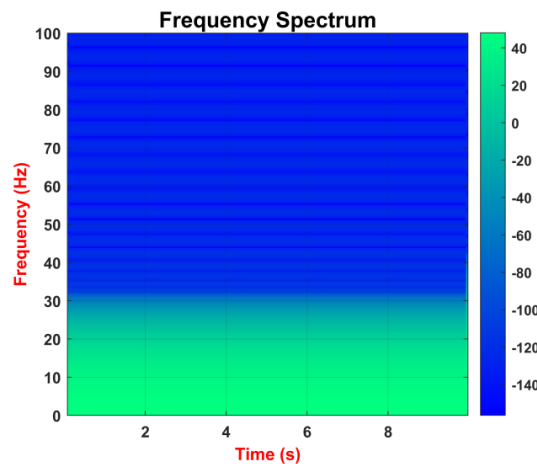
The fault specification is a symmetrical three-phase fault between phases (A, B, and C) and ground, a severe short circuit. Fault resistance values ( $R_{on}$ ) and ground resistance values ( $R_g$ ) were selected to be very low (0.001 ohms) to create an approximately zero impedance fault condition, thereby supplying very high fault currents. The fault scenario is used to test the responsiveness of systems and the effectiveness of fault detection techniques under realistic operating conditions.

Fig. 10 shows the analysis of the fast Fourier transform (FFT) signal before the fault. The spectral anomalies in Fig. 10 during the fault include missing data points. These anomalies could indicate a potential system failure or equipment damage. The FFT code within the PDC module detected the fault-induced disturbance and showed clear variations in spectral performance. The sudden change in the network can be explained by:

- (1) A short circuit that occurred quickly.
- (2) A rapid switching event that changed the network topology.
- (3) Abrupt disconnection and connection of the electrical load.
- (4) A phase imbalance corrected by protection systems.



(a) FFT signal of the Spectrum Analyzer for Voltage      (b) FFT signal of the Spectrum Analyzer for the Angle



(c) FFT signal of the Spectrum Analyzer for Frequency

Fig. 10 Analysis of electrical network faults using PDC and comparing Fourier signals before disturbance

Fig. 10 also shows the voltage frequency spectrum generated by the FFT algorithm within the PDC unit, illustrating how the voltage components are distributed across a wide frequency range and tracking their changes over time. The spectrum reveals a concentration of power around the fundamental frequencies without deviations or anomalous peaks, indicating the absence of disturbances or unusual frequency content. The figure also demonstrates the stability of the electrical behavior throughout the entire time period, reflecting the consistency of measurements transmitted from the PMUs. These outputs are used for comparison with phase angle and frequency analyses to confirm the system's stability across multiple indicators. Through this frequency analysis, the figure provides clear evidence of the system's operational integrity within a high-resolution, synchronous monitoring environment.

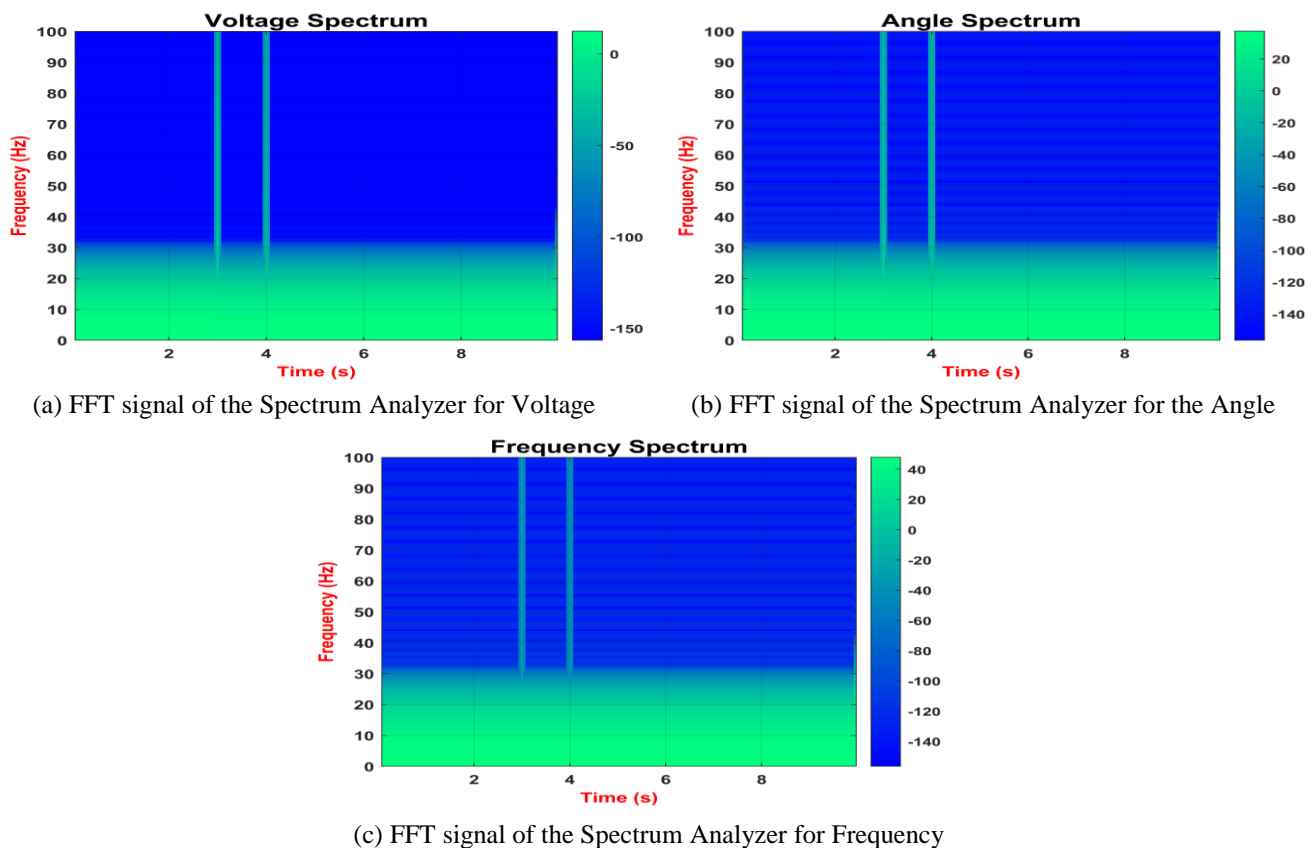


Fig. 11 Analysis of electrical network faults using PDC with comparison of Fourier signals after the disturbance

Fig. 11 shows the results of Fast Fourier Transform (FFT) analysis during a fault within the PDC unit algorithm, where the fault was detected at the moment of its occurrence, and again after 30 to 40 seconds. The figure provides clear evidence of a fault within a high-resolution, synchronous monitoring environment through changes in voltage, phase angle, and frequency as measured by the spectrum analyzer.

## 5.2. Features of Cloud Monitoring

Table 2 compares various studies using smart grid PMUs. It offers information on the system design employed in each study, the application environment, the fault detection technique, testing criteria, sampling rate, cloud integration, and data security. Figs. 12 and 13 illustrate the signals emitted by the PDC and sent to the IoT platform for remote monitoring. Hybrid monitoring (on-site and cloud-based) is essential for analyzing and protecting network behavior. Analyzing the data generated by remote monitoring enables the identification of potential future failures through visualization. This allows for efficient network management and reduced maintenance costs by making early maintenance decisions to prevent further failures and ensure network continuity. The ThingSpeak platform was used in this study. Fig. 12 shows the fault type and network voltage, current, and frequency values as observed through cloud monitoring.

Table 2 Comparison between my current study and previous studies on using PMUs in network monitoring

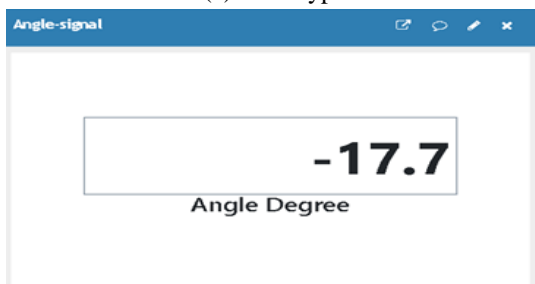
Study reference	System design	Application environment	Troubleshooting Method/Objective	Test Criteria	Sample rate	Cloud integration
Morato et al. [18]	PMUs with 5G for latency testing	Real-time simulation with 5G network	Fault simulation and delay response analysis	5G PMU Response Evaluation	Not mentioned	NO
Sufyan et al. [19]	Distributed PMUs and PDCs across multiple regions	Real Time Simulation	ADMM to improve synchronization between PDCs	Improved analysis accuracy with a limited time delay	Not mentioned	NO
Hojabri et al. [25]	PMUs in a Wide-Area Monitoring System (WAMS) distribution network	Simulation	Review of data quality challenges (not implemented in practice)	Not specified in detail	30-120 Hz	NO
Biswas et al. [26]	Open-source PMU data library for monitoring large networks	Collect and prepare actual data for PMU over two years.	Support for developing, modeling, and benchmarking algorithms	Data quality and event coverage	Variable depending on the event	NO
Cali et al. [27]	Development of PMUs	Applications in smart grids	Improve real-time system response with PMU	Real-time system status estimation	undefined	NO
Ruan et al. [28]	IEEE 14-Bus network +PMUs	Simulation / Edge-Computing	Spatiotemporal Graph Deep Learning (STGDL)-based detection of false data injection attacks	Detection Accuracy and F1 Score Analysis	60 Hz	NO
Allioua et al. [29]	Fully integrate PMU synchronization estimation into the cloud architecture	Theoretical and experimental analysis in a cloud environment	Evaluating the advantages and limitations of PMU (Pros/Cons)	Latency and reliability measurements	Up to 120 Hz	NO
proposed research	IEEE 14 Bus + 3 PMU, Local PDC, cloud monitoring	Real-time processing locally and then displaying to ThingSpeak	Fixed threshold detection: $\Delta V > 0.01$ pu, $\Delta A > 5^\circ$ , $\Delta F > 0.5$ Hz	SSR (Steady State Response) + FFT	50 Hz	(IoT / Cloud)



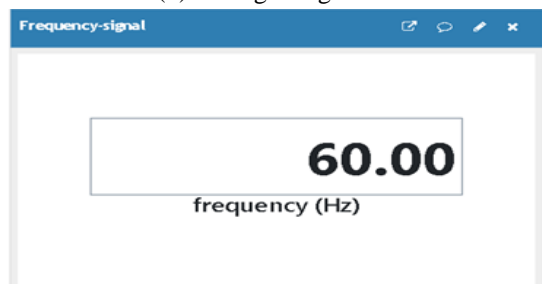
(a) Fault type



(b) Voltage magnitude



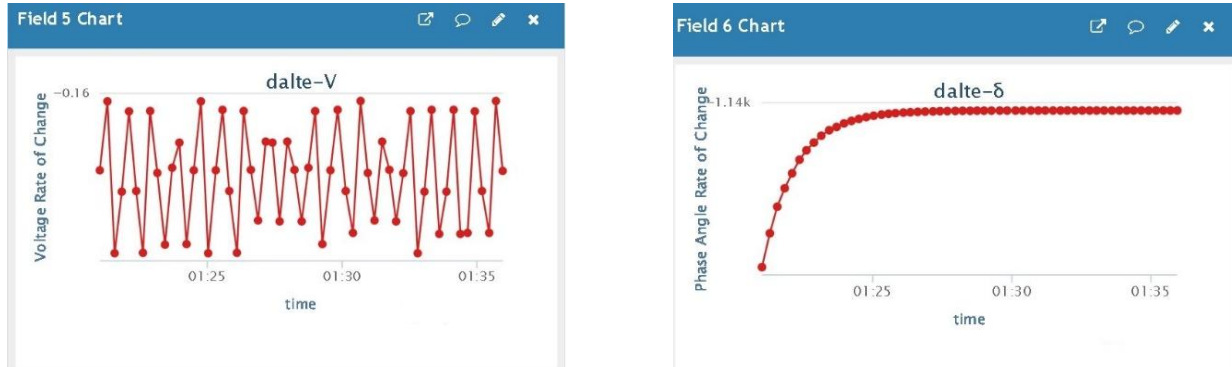
(c) Phase angle (angle degree)



(d) Frequency

Fig. 12 ThingSpeak presentation

Fig. 13 illustrates the time-rate-of-change analysis of voltage and phase angle ( $dV/dt$ ,  $d\delta/dt$ ) for monitoring the stability of the electrical grid using PMU data. This methodology is effective in detecting generation losses, sudden load changes, or the onset of faults. Fig. 13 (a) shows fluctuating voltage values, reflecting the sensitivity of the analysis algorithm in detecting minute changes that may indicate minor disturbances in the grid. Fig. 13 (b) shows the detection of phase angle changes, demonstrating a gradual stabilization towards a constant value over time, indicating system equilibrium after a short period of change. These figures contribute to evaluating the quality of concurrent measurements and the accuracy of the monitoring system's performance in cloud environments.



(a) Voltage Rate of Change  $dV/dt$

(b) Angle Rate of Change ( $d\delta/dt$ )

Fig. 13 Dynamic indicators of time-based rate of change ( $dV/dt$  and  $d\delta/dt$ ) for online monitoring

## 6. Conclusions

This paper presents the design and testing of an intelligent grid monitoring architecture under the IEEE 14-bus system test case using PMUs, multi-functional PDCs, and Cloud IoT platforms. The developed system effectively tracks grid behavior and enhances overall grid awareness through synchronized measurements in both steady-state and fault conditions, utilizing real-time processing. The proposed system offers scalability in terms of renewable energy sources within the context of modern power networks, featuring enhanced edge-cloud-level phasor analysis. The primary findings are:

- (1) Highly Sensitive Fault Detection: The system detected three-phase-to-ground faults in real-time, and this proves the reliability and responsiveness of the proposed PDC algorithm.
- (2) Multi-Signal Synchronized Processing: The PDC performed analysis of synchronized voltage, current, frequency, and phase angles, providing enhanced diagnostic resolution through simultaneous processing.
- (3) Dynamic Behavior Prediction: The monitoring system detected minor variations in the values of grid parameters, giving the first signs of the onset of instabilities in the system.
- (4) Cloud-Enabled Monitoring/Archiving: The relevant data streams were uploaded to the cloud successfully. This facilitated immediate visualization, analysis, and archiving of data in the cloud for future planning and forecasting.
- (5) Comprehensive Monitoring Compared to Traditional Methods: Unlike conventional methods of monitoring that are centered on single data parameters, comprehensive monitoring provides an overall perspective of electricity regarding various parameters of analysis.
- (6) Validated Performance Across Realistic Scenarios: The results shown in Figures 3 through 14 validate the system's capability to identify fault locations and sizes and sustain system stability in realistic operating scenarios.
- (7) Dual Layer Analysis Capability: The integration of local PDC processing and cloud-level analysis offers a strong two-tier system that can greatly benefit analyses regarding normal and faulty operating states, especially in distributed generation systems.

## Conflicts of Interest

The authors declare no conflict of interest.

## References

- [1] G. Sanchez-Ayala, J. R. Agüerc, D. Elizondo, and M. Lelic, "Current Trends on Applications of Pmus in Distribution Systems," 2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT), pp. 1-6, 2013.
- [2] A. G. Phadke and J. S. Thorp, "Phasor Measurement Units and Phasor Data Concentrators," Synchronized Phasor Measurements and Their Applications, pp. 93-105, 2008.
- [3] A. V. Varganova, V. R. Khramshin, and A. A. Radionov, "Improving Efficiency of Electric Energy System and Grid Operating Modes: Review of Optimization Techniques," Energies, vol. 15, no. 19, article no. 7177, 2022.
- [4] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart Grid—The New and Improved Power Grid: A Survey," IEEE Communications Surveys & Tutorials, vol. 14, no. 4, pp. 944-980, 2011.
- [5] N. Anang, M. S. A. Hamid, and W. M. W. Muda, "Simulation and Modelling of Electricity Usage Control and Monitoring System Using Thingspeak," Baghdad Science Journal, vol. 18, no. 2 (Suppl.), article no. 43, 2021.
- [6] S. Shankar, K. B. Yadav, A. Priyadarshi, and V. Rathore, "Study of Phasor Measurement Unit and Its Applications," Recent Advances in Power Systems: Select Proceedings of EPREC 2020, pp. 247-257, 2021.
- [7] A. Monti, C. Muscas, and F. Ponci, Phasor Measurement Units and Wide Area Monitoring Systems, Academic Press, 2016.
- [8] E. Rebello, L. Vanfretti, and M. S. Almas, "PMU-Based Real-Time Damping Control System Software and Hardware Architecture Synthesis and Evaluation," 2015 IEEE Power & Energy Society General Meeting, pp. 1-5, 2015.
- [9] A. G. Phadke, "Synchronized Phasor Measurements—A Historical Overview," IEEE/PES Transmission and Distribution Conference and Exhibition, vol. 1, pp. 476-479, 2002.
- [10] J. S. Bhonsle and A. S. Junghare, "An Optimal PMU-PDC Placement Technique in Wide Area Measurement System," 2015 International Conference on Smart Technologies and Management for Computing, Communication, Controls, Energy and Materials (ICSTM), pp. 401-405, 2015.
- [11] S. Kumar, M. K. Soni, and D. K. Jain, "Monitoring of Wide Area Power System Network with Phasor Data Concentrator (PDC)," International Journal of Information Engineering and Electronic Business, vol. 7, no. 5, pp. 20-26, 2015.
- [12] K. Wang, J. Wu, X. Zheng, J. Li, W. Yang, and A. V. Vasilakos, "Cloud-Edge Orchestrated Power Dispatching for Smart Grid with Distributed Energy Resources," IEEE Transactions on Cloud Computing, vol. 11, no. 2, pp. 1194-1203, 2022.
- [13] S. Saboo, "Unlocking the Value of Cloud-Enabled Emission Monitoring Systems for Sustainable Operations in the Oil and Gas Industry," Abu Dhabi International Petroleum Exhibition and Conference, article no. SPE-216053-MS, 2023.
- [14] I. B. F. Rahman, M. M. Islam, K. M. Muttaqi, A. H. Chowdhury, and T. S. Ustun, "Power System Faults Detection Using Machine Learning with PMU Based Wide Area Monitoring," 2024 13th International Conference on Electrical and Computer Engineering (ICECE), pp. 609-614, 2024.
- [15] D. Benavides, P. Arévalo, A. C. Ortega, F. Sánchez-Sutil, and E. Villa-Ávila, "Energy Management Model for a Remote Microgrid Based on Demand-Side Energy Control," Energies, vol. 17, no. 1, article no. 170, 2024.
- [16] V. Arenas-Ramos, F. Cuesta, V. Pallares-Lopez, and I. Santiago, "Software Integration of Power System Measurement Devices with AI Capabilities," Applied Sciences, vol. 15, no. 1, article no. 170, 2024.
- [17] J. G. Wright and S. D. Wolthusen, "A Re-transmission Algorithm for Phasor Data Concentrators for Resilience Enhancement of State Estimation," International Conference on Critical Information Infrastructures Security (CRITIS 2024), pp. 133-150, 2024.
- [18] A. Morato, G. Frigo, and F. Tramarin, "Fault Simulation in Phasor Measurement Units: A Study on System Reaction Time in A 5G Network Environment," Measurement: Sensors, vol. 38, Supplement, article no. 101445, 2025.
- [19] M. A. A. Sufyan, M. Zuhaib, M. A. Anees, A. Khair, and M. Rihan, "Implementation of PMU-Based Distributed Wide Area Monitoring in Smart Grid," IEEE Access, vol. 9, pp. 140768–140778, 2021.
- [20] M. Z. Islam, V. M. Vokkarane, and Y. Lin, "PMU Network Routing for Resilient Observability of Power Grids," ICC 2023-IEEE International Conference on Communications, pp. 4584–4590, 2023.
- [21] P. Castello, C. Muscas, and P. A. Pegoraro, "Statistical Behavior of PMU Measurement Errors: An Experimental Characterization," IEEE Open Journal of Instrumentation and Measurement, vol. 1, pp. 1-9, 2022.

- [22] K. R. Rao, D. N. Kim, J. J. Hwang, *Fast Fourier Transform – Algorithms and Applications*, Springer, 2011.
- [23] Y. Gong and N. Schulz, “Synchrophasor-Based Real-Time Voltage Stability Index,” 2006 IEEE PES Power Systems Conference and Exposition, pp. 1029-1036, 2006.
- [24] “University of Illinois at Urbana-Champaign, Illinois Center for a Smarter Electric Grid,” <https://icseg.iti.illinois.edu/power-cases/>, 2024.
- [25] M. Hojabri, U. Dersch, A. Papaemmanouil, and P. Bosshart, “A Comprehensive Survey on Phasor Measurement Unit Applications in Distribution Systems,” *Energies*, vol. 12, no. 23, article no. 4552, 2019.
- [26] S. Biswas, J. Follum, P. Etingov, X. Fan, and T. Yin, “An Open-Source Library of Phasor Measurement Unit Data Capturing Real Bulk Power Systems Behavior,” *IEEE Access*, vol. 11, pp. 108852–108863, 2023.
- [27] U. Cali, F. O. Catak, and U. Halden, “Trustworthy Cyber-Physical Power Systems Using AI: Dueling Algorithms for PMU Anomaly Detection and Cybersecurity,” *Artificial Intelligence Review*, vol. 57, no. 7, article no. 183, 2024.
- [28] J. Ruan, G. Fan, Y. Zhu, G. Liang, J. Zhao, F. Wen, et al., “Super-Resolution Perception Assisted Spatiotemporal Graph Deep Learning Against False Data Injection Attacks in Smart Grid,” *IEEE Transactions on Smart Grid*, vol. 14, no. 5, pp. 4035-4046, 2023.
- [29] C. Allioua, A. Mingotti, R. Tinarelli, L. Peretto, and G. Frigo, “Cloud-Based PMUs for Real-Time Power System Monitoring: Theoretical and Experimental Analysis,” 2023 IEEE 13th International Workshop on Applied Measurements for Power Systems (AMPS), pp. 01-06, 2023.



Copyright© by the authors. Licensee TAETI, Taiwan. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY-NC) license (<https://creativecommons.org/licenses/by-nc/4.0/>).