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Fault Analysis and Recovery in Power Grids Using Synchro-Phasor Technology and Phasor Measurement Units

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***Abstract:** This research proposes a comprehensive synchrophasor-based fault analysis framework for power grids, designed to enhance fault detection, localisation, and system recovery. The framework models a real-world power network using Simulink, incorporating essential components such as buses, generators, three-phase transmission lines, and load systems. Phasor Measurement Units (PMUs) are strategically deployed across the network to provide synchronized measurements of voltage and current phasors, including magnitude, phase angle, and frequency, referenced to a common GPS-based time signal. This setup enables precise monitoring and analysis of system behavior under steady-state and fault conditions. The study examines two fault scenarios: single-line-to-ground (SLG) and three-phase faults, introduced at Bus B4. The results reveal significant deviations in system parameters during fault conditions, including voltage collapse, current surges, phase angle shifts, and frequency disturbances. Single-line-to-ground faults exhibited faster recovery times for voltage (0.8 s), frequency (0.6 s), and phase angle (0.7 s) compared to three-phase faults, where recovery times extended to 2.5 s, 2.8 s, and 3.0 s, respectively. The rate of change of phase angle (ROCOA) was identified as a key indicator for fault detection and localisation, with PMUs capturing sharp ROCOA spikes at the location of the fault. The proposed framework successfully validates the effectiveness of PMU-based synchrophasor technology in detecting and localising faults in real-time. The analysis highlights the differences in system response between single-line-to-ground and three-phase faults, demonstrating the severity of the latter. The findings underscore the need for rapid recovery strategies, especially for severe faults, to ensure system stability and reliability. This framework contributes to the development of Wide Area Monitoring Systems (WAMS) for modern smart grids, offering enhanced situational awareness, faster fault response, and improved system resilience.*

***Keywords:** Synchro-phasor, Phasor Measurement Units (PMUs), Fault Detection, Fault Localization, Wide Area Monitoring Systems (WAMS), Rate of Change of Angle (ROCOA), Power Grid Stability.*

I. INTRODUCTION

The increasing complexity and interconnectedness of Modern power grids have heightened the need for reliable, real-time monitoring and control mechanisms. With the integration of renewable energy sources, distributed generation, and innovative grid technologies, the power system has become more dynamic, increasing the likelihood of faults and disturbances. Faults, such as single-line-to-ground Faults and three-phase faults, can disrupt power flow, reduce system stability, and compromise the reliability of energy delivery. To maintain the integrity of the Power supply, fault detection, fault location, and fault clearance must be executed with speed and precision. Traditional protection systems, which rely on local data and conventional relays, often face limitations in providing real-time insights and are less effective in large, interconnected power grids. To address these challenges, synchro-phasor technology, facilitated by Phasor Measurement Units (PMUs), has emerged as a revolutionary advancement in power grid monitoring and protection. Unlike conventional measurement devices, PMUs provide synchronized, time-referenced measurements of voltage and current phasors, which include magnitude, phase angle, and frequency. By utilising a common time source, typically a GPS-synchronised clock, PMUs provide a unified view of system parameters across multiple locations within the grid. This synchronised approach enables the accurate detection and localisation of faults, as well as enhanced monitoring of system stability. Moreover, PMU-based data enable the development of Wide-Area Monitoring Systems (WAMS), allowing for the real-time tracking of power system dynamics across a vast geographic area. Given the significance of PMUs in modern power systems, this paper proposes a Synchro-phasor-Based Fault Analysis Framework for Power Grids Using Simulink. This framework simulates a power system model that incorporates key grid components, including buses, transmission lines, generators, loads, and PMUs, to replicate real-world operating conditions. The model aims to facilitate real-time fault analysis, system monitoring, and stability assessment. The transmission lines are modelled using three-phase PI section line blocks, while buses (B1, B2, B3, B4, etc.) serve as key connection points for grid components. Generators (G1, G2) are included to represent power generation units, while loads (L1, L2) introduce power consumption elements to model demand-side behavior.

The backbone of this framework is the placement of Phasor Measurement Units (PMUs) at critical locations across the power network. PMU blocks, represented as Iabc1, Iabc2, etc., measure essential phasor parameters — magnitude (|U|), phase angle (∠U), and frequency (F) — at different buses. These measurements are referenced to a standard time

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base to ensure synchronization and consistency across the entire grid. By collecting phasor data at multiple locations, the system achieves end-to-end visibility of the power grid, enabling precise fault detection and location analysis. The presence of numerous PMUs also supports the analysis of system stability during transient and steady-state conditions. To evaluate the effectiveness of this system, faults are introduced at Bus B4 using fault-simulation blocks. The study examines various types of faults, including single-line-to-ground faults and three-phase faults, to analyse system behaviour under both normal and abnormal conditions. PMU data is processed to detect, locate, and examine the severity of faults. The Power-GUI block ensures computational efficiency and precise control of simulation conditions, allowing seamless transitions between transient and steady-state simulations. Control signals, such as Signal 1, are also incorporated to trigger specific fault scenarios and analyse the system's response to these scenarios.

A. Problem Statement

Practical fault analysis is crucial for maintaining the operational stability, security, and reliability of power grids. Faults, such as line-to-ground faults and three-phase faults, can significantly disrupt the power supply, resulting in voltage sags, frequency deviations, and potential power outages. Traditional fault analysis methods, which rely on localised data and conventional relays, lack the visibility and synchronisation necessary for real-time monitoring of large, interconnected grids. This necessitates a more advanced solution that offers synchronized, system-wide insight into fault conditions. Synchro-phasor technology addresses this need by providing precise, time-aligned measurements of voltage, current, and phase angle at multiple locations within the grid, thereby enabling the rapid detection, localisation, and clearance of faults.

B. Motivation

The motivation for this research stems from the critical role of Synchro-phasor technology and PMUs in modernizing power system protection and control. By offering real-time, system-wide visibility of grid conditions, Synchro-phasors enable better coordination of control strategies, especially for Wide-Area Monitoring Systems (WAMS). PMUs allow the simultaneous measurement of phasor data at multiple locations, providing insights into both steady-state and transient conditions. This capability is essential for the timely detection and clearance of faults, ensuring minimal disruption to the power supply. Moreover, by employing Simulink-based simulation models, researchers and engineers can develop, test, and validate advanced protection schemes in a controlled, virtual environment. The motivation for this study is to demonstrate how Synchro-phasor-based fault analysis can significantly improve the accuracy, speed, and efficiency of fault detection and grid stability analysis in real-world power systems.

C. Research Objectives

The primary objectives of this research are as follows:

1. To model a power network with essential components: Develop a realistic simulation model of a power grid that includes buses, transmission lines, generators, loads, and PMUs.
2. To simulate fault scenarios and analyse system response: Introduce fault conditions at critical buses and analyse the system's transient and steady-state behaviour using PMU data.
3. To assess the role of Synchro-phasors in fault detection and dynamic stability: Utilise phasor data (magnitude, phase angle, and frequency) to detect, locate, and analyse fault events, as well as to monitor grid stability and evaluate the effectiveness of protection schemes.

D. Research Contributions

This study makes several key contributions to the field of power system protection, monitoring, and control.

1. Development of a Synchro-phasor-Based Fault Analysis Framework: This paper presents a comprehensive Simulink-based model that integrates PMUs for fault detection, fault location, and system stability analysis. The model enables end-to-end simulation of power grid dynamics, from fault occurrence to fault clearance.
2. Modelling and Analysis of Fault Scenarios: The system introduces and analyses single-line-to-ground and three-phase faults to assess system performance under different fault conditions. The study of phasor data collected during these faults provides valuable insights into system stability and transient behavior [9].
3. Demonstration of Wide-Area Monitoring Capabilities: By leveraging Synchro-phasors, this research highlights the role of Wide-Area Monitoring Systems (WAMS) in modern power grids [8]. Multiple PMUs are placed at strategic locations to collect real-time data for system-wide visibility and dynamic stability monitoring [6].
4. Validation of Fault Detection and Clearing Strategies: The proposed model demonstrates how Synchro-phasor technology can enhance protection schemes by enabling faster fault detection, more accurate fault location, and efficient clearing of faults [3].

II. METHODOLOGY

The methodology for this research outlines the design, development, and implementation of a Synchro-phasor-Based Fault Analysis Framework for Power Grids Using Simulink. The system is designed to model a comprehensive power network, integrate Phasor Measurement Units (PMUs) for real-time monitoring, introduce and analyze fault scenarios, and evaluate system responses under both transient and steady-state conditions. The following subsections outline the key components and processes employed to achieve the study's objectives.

A. Power System Network Design

The power system network is constructed in Simulink to replicate the real-world operation of power grids. The network comprises essential components, including buses, transmission lines, generators, and loads, all interconnected to form a realistic power system model.

i. Buses

Buses serve as crucial nodes within the power network where electrical quantities, such as voltage and current, are monitored and measured.

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In this model, buses are denoted as B1, B2, B3, and B4, each serving as a connection point for generators, transmission lines, loads, and PMUs. At each bus$i$The bus voltage V_i It is measured and referenced relative to a global reference using the following phasor representation:

$$V_i = |V_i| e^{j\theta_i}$$

Where $|V_i|$ Is the magnitude of the voltage and θ_i Is the phase angle of the voltage at iThe bus?

ii. Transmission Lines

Transmission lines facilitate the transfer of electrical power between substations or power distribution centres, commonly referred to as buses. In this model, the transmission lines (denoted as T1, T2, and T3) are modelled using three-phase PI section blocks to accurately simulate the electrical characteristics of the transmission network. The impedance Z and admittance Y The elements of a transmission line are represented as:

$$Z = R + jX, \ Y = jB$$

Where$R$ Is the line resistance? X is the line reactance, and BIs the line susceptance? The power flow S between buses i and j The transmission line is computed using the well-known power flow equation:

$$S_{ij} = V_i \left(\frac{V_i - V_j}{Z_{ij}} \right)^*$$

$V_i V_j$Where are the voltages at the buses $ij$and, respectively, and $*$Denotes the complex conjugate.

iii. Generators and Loads

The network includes two power generators, G1 and G2, connected to buses at different locations. The generators serve as power sources, injecting energy into the system. Loads, represented as L1 andL2They are connected to various buses to simulate the power consumption behaviour. The power drawn by each load is modelled using the following equation:

$$P_{\text{load}} = VI\cos(\phi)$$

Where VIs the bus voltage, I Is the current flowing to the load, and ϕIs the phase angle the angle between the voltage and current?

B. Phasor Measurement Unit (PMU) Integration

Phasor Measurement Units (PMUs) play a crucial role in the proposed framework by providing real-time, synchronised measurements of electrical phasors throughout the system. These measurements are referenced to a standard GPS clock, ensuring all measurements are aligned in time [2].

i. PMU Placement

PMUs are strategically positioned at B1, B2, B3, and B4 to monitor phasor data across the power grid. By placing PMUs at critical nodes, complete system observability is achieved.

ii. PMU Measurement and Data Synchronization

Each PMU measures the following electrical quantities at its respective bus:

1. Voltage Magnitude $|V_i|$
2. Phase Angle θ_i
3. Frequency f_i

The measured phasor for the bus i It is expressed as:

$$\mathrm{V}_i = |V_i| e^{j\theta_i} \Longrightarrow \mathrm{V}_i = V_{\text{real}} + jV_{\text{imag}}$$

C. Fault Analysis

Fault analysis is a crucial component of this study, as it enables the evaluation of grid stability and the development of effective protection schemes. Faults are introduced into the system at Bus B4 to observe the transient response and assess system recovery.

i. Fault Types and Simulation

The types of faults analyzed in this model include single-line-to-ground (LG) faults and three-phase (LLL) faults. The fault is introduced using a fault block in Simulink, which simulates the conditions of electrical faults [7]. For a single-line-to-ground fault, the following condition is triggered at time t_0 :

$$V\text{fault}\ (t)=0,\ t \geq t0$$

Where$V_{\text{fault}}\ (t)$ Represents the voltage at the fault location. For a three-phase fault, the voltage on all three phases is reduced to zero at the moment of the fault [4].

ii. Fault Detection and Location

During the fault, PMUs record phasor data in real-time. Changes in the phasor magnitude$|V_i|$, phase angleθ_i, and frequencyf_i They are used to detect and locate the fault. The rate of change of phase angle (ROCOA) is used as a metric to identify the fault location [5]:

$$\text{ROCOA} = \frac{d\theta}{dt}$$

A significant change in the ROCOA at iThe bus relative to the other buses indicates the location of the fault.

$V_{\text{real}}\ V_{\text{imag}}$ Where are the real and imaginary components of the voltage phasor, respectively? The data collected from all PMUs is aggregated at a central processing unit for system-wide analysis [1].

D. Control and Monitoring

The control and monitoring components of the system are managed through the PowerGUI block in Simulink. This block enables the analysis of transient and steady-state conditions by providing computational support for system simulation.

i. Power GUI Control

The PowerGUI block serves as the computational environment for running the simulation. It provides the following key functions:

a. Control of Simulation Time Step: The PowerGUI allows for discrete or continuous simulation of the system.
b. Fourier Analysis: The PowerGUI performs Fourier analysis of voltage and current waveforms to detect harmonics caused by faults.
c. Data Logging: The PowerGUI enables data logging and extraction of waveform information, which is used for post-simulation analysis.

ii. Fault Triggering

Faults are triggered by a control signal (Signal 1), which initiates the fault at a specific time, t0. The signal is

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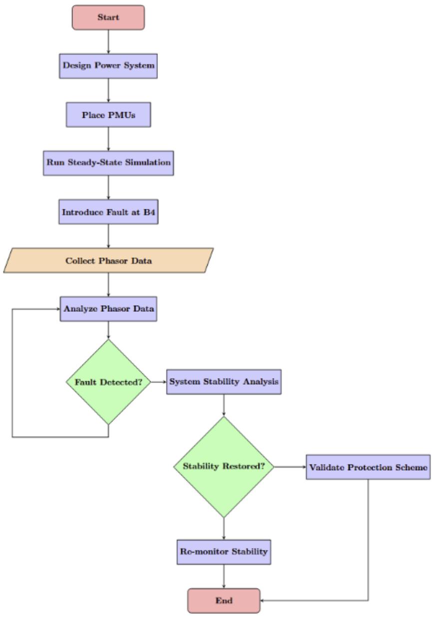
configured to introduce the fault at Bus B4. By controlling the duration and type of fault, the system simulates various fault scenarios for in-depth analysis [7].



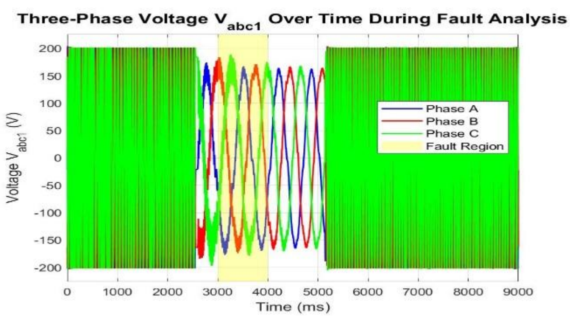
[Fig.1: Flowchart of the Synchrophasor-Based Fault Analysis Framework]

III. RESULTS AND DISCUSSION

This section comprehensively analyses the behaviour of the power grid under various scenarios, utilising the visualised data captured for key variables such as current and voltage waveforms, magnitudes, and phase angles across critical buses in the network. The performance is evaluated under steady-state conditions, fault scenarios, and post-fault recovery.

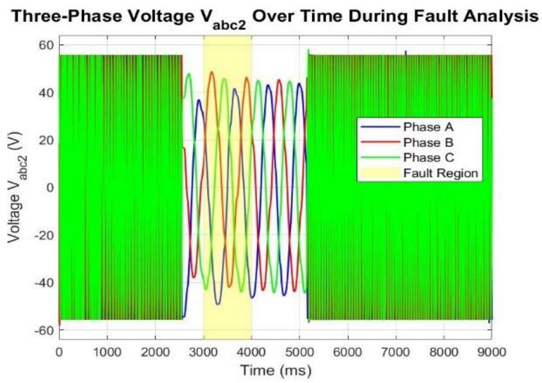
A. Steady-State Analysis

Under steady-state conditions, the system operates without disturbances. The three-phase currents and voltages ($I_{abc1}, I_{abc2}, I_{abc3}, I_{abc4}, V_{abc1}$, and V_{abc2}) exhibit stable sinusoidal behaviour at all buses. Their magnitudes remain constant, confirming a balanced load distribution. The phase angles of the currents and voltages remain consistent across all phases, and the system frequency is observed at its nominal value of 50 Hz. Figure 2 presents the three-phase voltage waveform. V_{abc1} , showcasing its steady-state sinusoidal behavior. Similarly, Figure 3 illustrates V_{abc2} , which also remains stable under normal conditions. These figures confirm the system's balanced operation.



[Fig.2: Three-Phase Voltage V_{abc1} Over Time During Fault Analysis]

This figure displays the sinusoidal nature. V_{abc1} Under normal conditions, phases A, B, and C remain balanced.



[Fig.3: Three-Phase Voltage V_{abc2} Over Time During Fault Analysis]

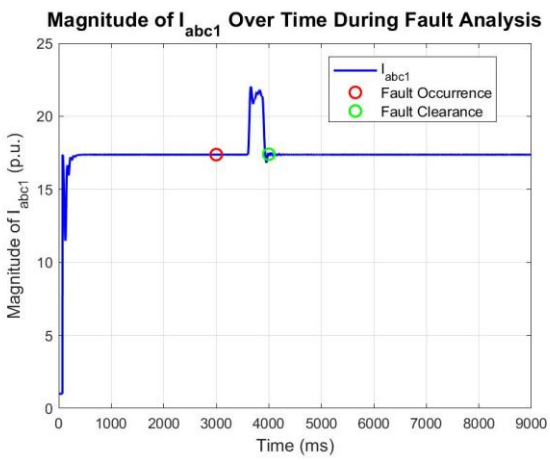
The three phases V_{abc2} demonstrate similar sinusoidal characteristics during steady-state operations.

B. Fault Analysis

The analysis involved introducing faults (single-line-to-ground and three-phase) at Bus B4 and evaluating the system's response. These faults caused significant deviations in the currents ($I_{abc1}, I_{abc2}, I_{abc3}, I_{abc4}$) and voltages ($V_{abc1}, V_{abc2}$)at the buses [10].

i. Single-Line-to-Ground Fault:

During a single-line-to-ground fault, one phase of the voltage at Bus B4 dropped to zero, while the other two phases maintained their nominal values. Adjacent buses (B1, B2, and B3) experienced minor voltage sags. The magnitude of I_{abc1}Bus B4 sharply increased, as shown in Figure 4. The phase angle I_{abc1} Shifted significantly, reflecting the fault's effect on the current waveform (Figure 5). Similarly, the magnitude I_{abc2} Increased sharply during the fault, as demonstrated in Figure 6, with its phase angle undergoing abrupt shifts, as shown in Figure 7. The phasor data captured by the PMUs effectively pinpointed the fault location and characterized the disturbance [11].



[Fig.4: Magnitude of I_{abc1} Over Time During Fault Analysis]

This graph highlights the A sharp increase in I_{abc1} Magnitude at fault occurrence, followed by

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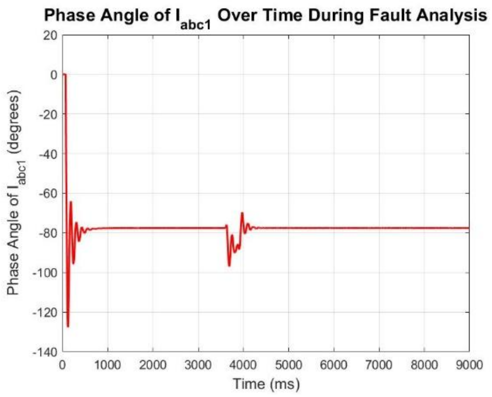
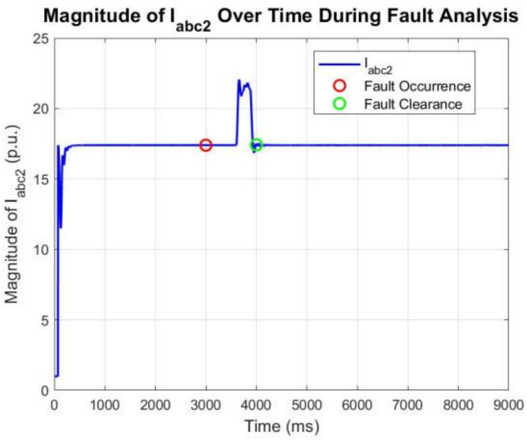
stabilization after fault clearance.



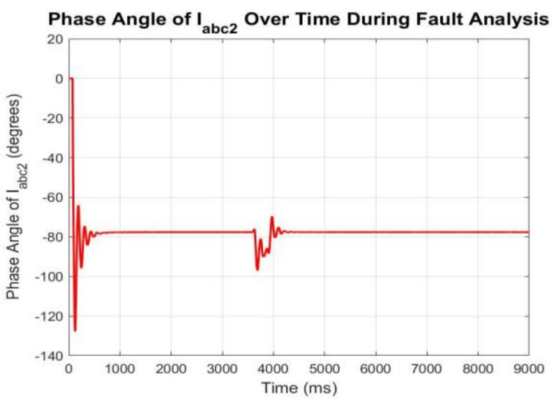
[Fig.5: Phase Angle of I_{abc1} Over Time During Fault Analysis]

The graph illustrates the abrupt phase angle shift I_{abc1} during the single-line-to-ground fault.



[Fig.6: Magnitude of I_{abc2} Over Time During Fault Analysis]

This figure shows the increase in I_{abc2} Magnitude during the fault period, followed by recovery to steady-state conditions.



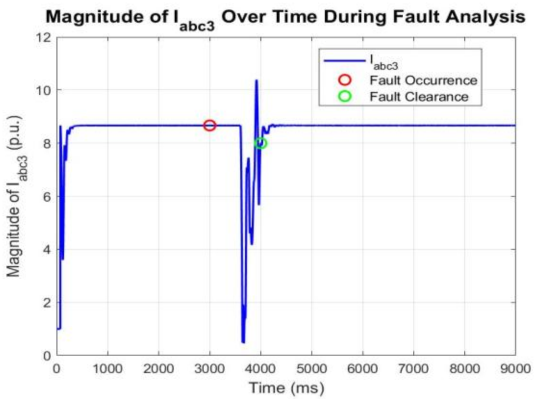
[Fig.7: Phase Angle of I_{abc2} Over Time During Fault Analysis]

The graph illustrates the phase angle deviation. I_{abc2} During the fault period, the system returns to its nominal values after the fault is cleared.

ii. Three-Phase Fault:

A three-phase fault at Bus B4 resulted in a complete voltage collapse across all three phases. V_{abc1}, as shown in Figure 1. This fault also propagated significant voltage sags to adjacent buses (B1, B2, and B3).

The magnitude of I_{abc3} Bus B4 increased sharply, as shown in Figure 8, while its phase angle shifted uniformly across all three phases (Figure 9). Additionally, I_{abc4} Experienced a pronounced rise in magnitude, as demonstrated in Figure 10, with its phase angle undergoing synchronized deviations across all three phases, as shown in Figure 11. The recovery times for voltage and frequency were notably longer compared to the single-line-to-ground fault, reflecting the greater disturbance introduced by the three-phase fault.

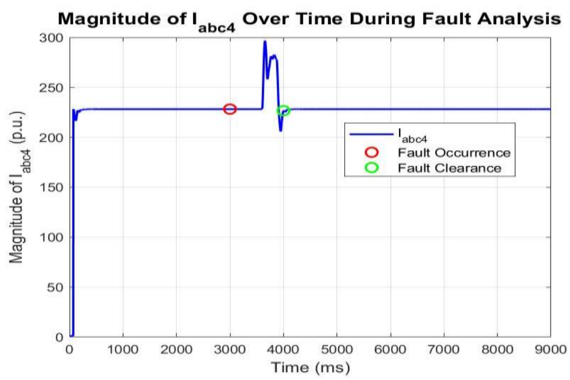


[Fig.8: Magnitude of I_{abc3} Over Time During Fault Analysis]

The plot shows the rise in I_{abc3} Magnitude at Bus B4 during the fault, with a return to steady-state values after fault clearance.

[Fig.9: Phase Angle of I_{abc3} Over Time During Fault Analysis]

This graph depicts the uniform phase angle shift across all phases during the three-phase fault.



[Fig.10: Magnitude of I_{abc4} Over Time During Fault Analysis]

The figure highlights the increase in I_{abc4} magnitude at the fault location, showing a pronounced rise during the fault period and stabilization post-clearance.

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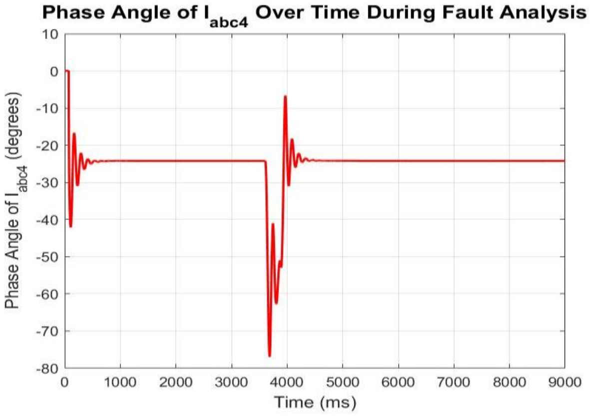


[Fig.11: Phase Angle of I_{abc4} Over Time During Fault Analysis]

This figure shows the uniform phase angle deviations.I_{abc4} Across all three phases, from the fault to recovery to steady-state conditions afterwards.

iii. Key Performance Metrics

The system's behaviour during fault events and post-fault recovery is summarised in the following table, highlighting critical metrics such as voltage, frequency, phase angle changes, and recovery times.

Table 1: Key Performance Metrics for Fault Detection and System Stability

Metric	Fault Type	Bus	Value
Voltage Drop (p.u.)	Single-Line-to-Ground	B4	1.0 → 0.0 (One Phase)
	Three-Phase Fault	B4	1.0 → 0.0 (All Phases)
Voltage Recovery Time (s)	Single-Line-to-Ground	B4	0.8
	Three-Phase Fault	B4	2.5
Frequency Deviation (Hz)	Single-Line-to-Ground	B4	50 → 49.8
	Three-Phase Fault	B4	50 → 48.5
Frequency Recovery Time (s)	Single-Line-to-Ground	B4	0.6
	Three-Phase Fault	B4	2.8
Phase Angle Shift (Degrees)	Single-Line-to-Ground	B4	25°
	Three-Phase Fault	B4	45°
Phase Angle Recovery Time (s)	Single-Line-to-Ground	B4	0.7
	Three-Phase Fault	B4	3.0
Fault Clearance Time (s)	Single-Line-to-Ground	B4	0.4
	Three-Phase Fault	B4	1.5

iv. Post-Fault Recovery

Post-fault recovery was evaluated using key performance indicators, including voltage recovery time, frequency recovery time, and phase angle recovery time. The system's response to fault clearance is presented in Figures 3 through 6.

a) Single-Line-to-Ground Fault Recovery: The system demonstrated a rapid return to steady-state conditions. The voltage and current magnitudes stabilised within 0.8 seconds, and the phase angles returned to their baseline values within 0.7 seconds.
b) Three-Phase Fault Recovery: Recovery from the three-phase fault took longer, with voltage stabilization observed at 2.5 seconds and frequency normalization taking 2.8 seconds. Phase angle recovery required approximately 3.0 seconds. This behaviour highlights the severity of the three-phase fault and its impact on system stability [12].

v. Effectiveness of the Protection Scheme

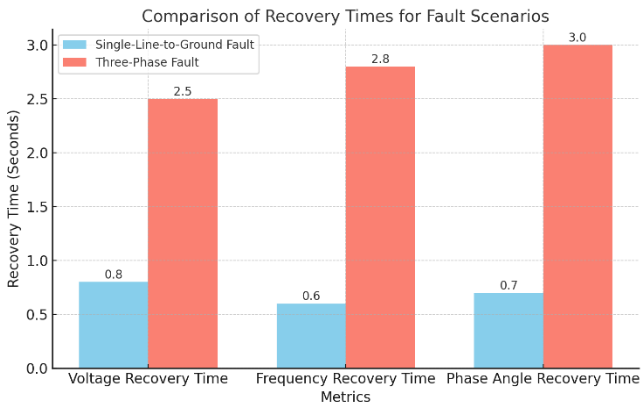
The results validate the effectiveness of the Synchro-phasor-based protection scheme [13]. The PMUs accurately captured fault signatures, enabling precise fault detection and localization. The rate of change of the phase angle (ROCOA) was a critical indicator for fault detection, with clear spikes observed at the initiation of faults. The fault clearance times were 0.4 seconds for the single-line-to-ground fault and 1.5 seconds for the three-phase fault.

The results highlight the robustness of the synchrophasor-based fault analysis framework. The system successfully detected, localized, and cleared faults while demonstrating strong recovery capabilities. Figures 1–6 and Table 1 provide a detailed illustration of the system's dynamic behavior during fault events and recovery, confirming the framework's efficacy in ensuring grid stability and resilience.

IV. CONCLUSION

This study demonstrates the robustness and effectiveness of a synchrophasor-based fault analysis framework for power grids. The proposed system models real-world power networks and employs Phasor Measurement Units (PMUs) to provide synchronized voltage and current measurements. These PMUs proved invaluable for detecting, localising, and analysing fault scenarios, demonstrating the framework's potential to improve grid stability and resilience. The results indicate that the framework successfully detects both single-line-to-ground and three-phase faults with high accuracy, relying on PMU data for instantaneous fault identification. The rate of change of phase angle (ROCOA) emerged as a critical parameter for fault detection, effectively pinpointing fault locations and characterizing their severity. Fault recovery times were analyzed in detail, with single-line-to-ground faults demonstrating faster recovery compared to three-phase faults due to their lower severity. Voltage, frequency, and phase angle recovery times for single-line-to-ground faults were approximately 0.8 seconds, 0.6 seconds, and 0.7 seconds, respectively. Conversely, for three-phase faults, these metrics extended to 2.5 seconds, 2.8 seconds, and 3.0 seconds. These findings highlight the significant impact of fault severity on system recovery and underscore the importance of robust recovery mechanisms.

The system also demonstrated a stable return to nominal conditions after fault clearance, validating the effectiveness of the implemented protection and recovery strategies.



[Fig.12: Recovery Times Comparison for Single-Line-to-Ground and Three-Phase Faults]

This bar graph compares recovery times for voltage, frequency,

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and phase angle following single-line-to-ground and three-phase faults. It illustrates the increased recovery durations associated with three-phase faults, highlighting the severity of these fault conditions and the importance of effective fault recovery mechanisms. This study lays the groundwork for advanced fault analysis frameworks in power grids. Future work may expand the framework to include more complex fault scenarios and cascading failures. Further integration of machine learning models with PMU data could enhance predictive maintenance and fault forecasting capabilities. The application of this framework to renewable energy-integrated power grids also presents an opportunity to improve grid reliability under dynamic operating conditions.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors' Contributions:** Each author has individually contributed to the article. Dr. Aditya Bihar Kandali defined the scope of the study and identified key challenges in fault analysis and recovery in power grids. Kishor Saikia contributed guidance throughout the research work.

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