



Adaptive Microgrid Protection System

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KEYWORDS

Microgrid, Adaptive Protection, ESP32, Fault Detection, Renewable Energy, Smart Grid

ABSTRACT

The rapid integration of renewable energy sources such as solar and wind into microgrids has introduced significant challenges in power system protection due to bidirectional power flow, varying fault levels, and dynamic operating conditions. This paper presents the design and implementation of an Adaptive Microgrid Protection System (AMPS) that ensures reliable fault detection and isolation under both normal and abnormal conditions. The proposed system employs a microcontroller (ESP32) to continuously monitor voltage and current parameters using sensors. It detects faults such as phase faults, short circuits, and source failures, and dynamically isolates faulty sections using relay-based control. The system also incorporates automatic source switching between grid, solar, and wind to maintain uninterrupted power supply. Real-time status monitoring is provided through LCD display, LEDs, and buzzer alerts. Experimental results demonstrate improved system reliability, reduced downtime, and enhanced adaptability compared to conventional protection schemes. The system is suitable for smart grid applications and future integration with AI-based fault prediction systems.

1. INTRODUCTION

The global transition toward sustainable and decentralized energy systems has significantly accelerated the adoption of microgrids, which integrate distributed energy resources (DERs) such as solar photovoltaic (PV) systems, wind turbines, energy storage units, and conventional utility grids. Microgrids are capable of operating in both grid-connected mode

and islanded mode, thereby enhancing system reliability, resilience, and energy efficiency. These systems play a crucial role in modern power infrastructure, particularly in rural electrification, smart cities, and renewable energy integration.

Despite their advantages, microgrids introduce substantial challenges in protection system design due to their dynamic and complex nature. Unlike traditional

power systems, which assume unidirectional power flow and relatively stable fault current levels, microgrids exhibit bidirectional power flow, frequent topology changes, and varying fault contributions from inverter-based and rotating generation sources. In particular, renewable energy sources such as solar PV and wind turbines are inherently intermittent and are typically interfaced through power electronic converters, which significantly limit fault current levels. This variability reduces the effectiveness of conventional protection schemes.

Traditional protection techniques, including overcurrent protection and distance protection, are designed based on fixed system parameters and predefined fault conditions. These methods rely on predictable fault current magnitudes and consistent network configurations. However, in a microgrid environment, fault current levels vary depending on operating mode (grid-connected or islanded), source availability, and system configuration. As a result, conventional protection schemes may suffer from maloperation, delayed tripping, or lack of selectivity, potentially leading to equipment damage, reduced system stability, and unnecessary outages.

To overcome these limitations, adaptive protection systems have emerged as a promising solution. Adaptive protection involves dynamically adjusting relay settings and protection strategies in real time based on continuously monitored system parameters. By incorporating intelligent control algorithms, communication interfaces, and embedded systems, adaptive protection ensures accurate fault detection and isolation under varying operating conditions. This approach enhances system reliability, minimizes downtime, and improves overall protection coordination in microgrids.

Recent advancements in embedded systems and IoT technologies have enabled the practical implementation of adaptive protection schemes using microcontrollers such as ESP32 and Arduino platforms. These controllers can process real-time data from sensors, execute decision-making algorithms, and control switching devices such as relays. Furthermore, integration with communication technologies allows remote monitoring and control, aligning with the requirements of modern smart grid systems.

In this context, the present work proposes the design and implementation of an Adaptive Microgrid Protection System (AMPS) that integrates multiple energy sources, including solar, wind, and the utility grid. The system continuously monitors electrical parameters such as voltage and current using sensors interfaced with a microcontroller. Based on real-time analysis, it detects various fault conditions, including phase faults, source failures, and load disturbances. Upon fault detection, the system isolates the affected section using relay control and automatically switches to an alternative healthy power source, ensuring uninterrupted power supply.

Additionally, the proposed system incorporates user-friendly monitoring features, such as LCD displays, LED indicators, and buzzer alerts, to provide real-time system status and fault notifications. The implementation also supports communication capabilities for remote monitoring, making it suitable for smart grid applications.

The main contributions of this work are summarized as follows:

- Development of a real-time adaptive protection system for microgrids
- Integration of multiple renewable and conventional energy sources
- Implementation of automatic fault detection and isolation mechanisms
- Design of adaptive source switching strategy for uninterrupted power supply
- Demonstration of a low-cost, hardware-based prototype using ESP32

The remainder of this paper is organized as follows: Section II presents the literature review, Section III describes the system design and methodology, Section IV discusses experimental results, and Section V concludes the paper with future research directions.

II. LITERATURE SURVEY

The rapid integration of distributed energy resources (DERs) such as solar photovoltaic systems, wind turbines, and energy storage units has significantly transformed conventional power systems into active and dynamic microgrids. While these systems improve efficiency, sustainability, and reliability, they also introduce major challenges in protection due to bidirectional power flow, varying fault current levels,

and frequent changes in system configuration. As a result, traditional protection techniques are no longer sufficient, and extensive research has been carried out to develop advanced protection strategies for microgrids [5], [18], [19].

Overcurrent protection is one of the most widely used techniques due to its simplicity, low cost, and ease of implementation. However, its effectiveness in microgrids is limited because fault current levels vary depending on operating conditions. Mahat et al. proposed an adaptive overcurrent protection scheme and demonstrated that fixed relay settings are inadequate in systems with distributed generation [1]. Similarly, Najy et al. highlighted coordination challenges in microgrids operating under both grid-connected and islanded modes, emphasizing the need for adaptive relay settings [2]. Coffele et al. introduced an adaptive relay coordination method that dynamically updates relay parameters based on real-time system conditions [3]. Ferreira et al. proposed a relay setting group approach to improve selectivity and reliability [4]. Despite these developments, overcurrent protection still suffers from reduced sensitivity and coordination issues due to bidirectional power flow and variable fault currents [5].

Distance protection, which is based on impedance measurement, offers faster and more selective fault detection compared to overcurrent methods. However, its performance is also affected by the presence of distributed generation. Brahma and Girgis developed an adaptive protection scheme and showed that impedance variation affects relay accuracy [6]. Memon and Kauhaniemi provided a comprehensive review highlighting that topology changes and low fault current levels degrade the performance of distance protection [7]. Zamani et al. proposed a microprocessor-based relay for low-voltage microgrids, improving detection speed and adaptability [8]. However, Hooshyar and Sanaye-Pasand demonstrated that distributed generation can lead to relay misoperation due to impedance variation and reverse power flow [9]. Manditereza and Bansal further discussed practical challenges such as fault resistance and system reconfiguration, which affect relay performance [10].

To overcome the limitations of conventional protection methods, researchers have explored differential protection and communication-based

protection schemes. Differential protection provides high accuracy by comparing current values at different points in the system, but it requires synchronized measurements and reliable communication infrastructure. Dewadasa et al. proposed a differential protection scheme for microgrids, which improved fault detection accuracy but increased system complexity [11]. Communication-assisted protection methods further enhance coordination between relays through real-time data exchange. The use of synchronized phasor measurements, as discussed by Phadke and Thorp, improves protection performance but adds to system cost and complexity [14]. Additionally, communication-based adaptive protection schemes have been proposed to dynamically adjust protection settings, though they depend heavily on communication reliability [15].

In recent years, intelligent protection techniques based on artificial intelligence (AI) and machine learning (ML) have gained significant attention. Samantaray proposed a decision tree-based method for fault detection and classification, enabling faster and more accurate fault identification [12]. Similarly, Alam et al. applied optimization techniques such as differential evolution to improve relay coordination in microgrids [13]. AI-based systems offer advantages such as predictive fault detection, adaptive decision-making, and improved reliability. However, these methods require large datasets, training processes, and computational resources, which may limit their practical implementation in cost-sensitive applications.

Despite the advancements in microgrid protection, several research gaps still exist. Many existing systems rely on fixed protection settings that cannot adapt to dynamic operating conditions. Maintaining coordination between protective devices remains a challenge due to varying fault levels and system configurations. The integration of renewable energy sources reduces fault current levels and affects impedance, leading to incorrect relay operation. Additionally, bidirectional power flow complicates fault detection, as traditional protection systems are designed for unidirectional flow [16], [17]. Furthermore, a significant portion of existing research is simulation-based, with limited real-time hardware implementation [7], [15].

To address these challenges, there is a need for a real-time adaptive protection system capable of

dynamically responding to changing microgrid conditions. The proposed Adaptive Microgrid Protection System focuses on continuous monitoring of system parameters, intelligent fault detection, and automatic isolation of faulty sections. By integrating multiple energy sources and implementing adaptive control using a microcontroller, the system ensures reliable operation, fast fault response, and uninterrupted power supply. This approach provides a practical and cost-effective solution for modern microgrid protection and contributes to the advancement of smart grid technologies.

3. SYSTEM DESIGN AND METHODOLOGY

The proposed Adaptive Microgrid Protection System (AMPS) is designed to ensure reliable, efficient, and real-time protection of a microgrid integrating multiple energy sources such as solar, wind, and the utility grid. The system follows a centralized embedded control architecture using an ESP32 microcontroller, which continuously monitors system parameters and performs adaptive decision-making for fault detection and isolation.

A. System Architecture

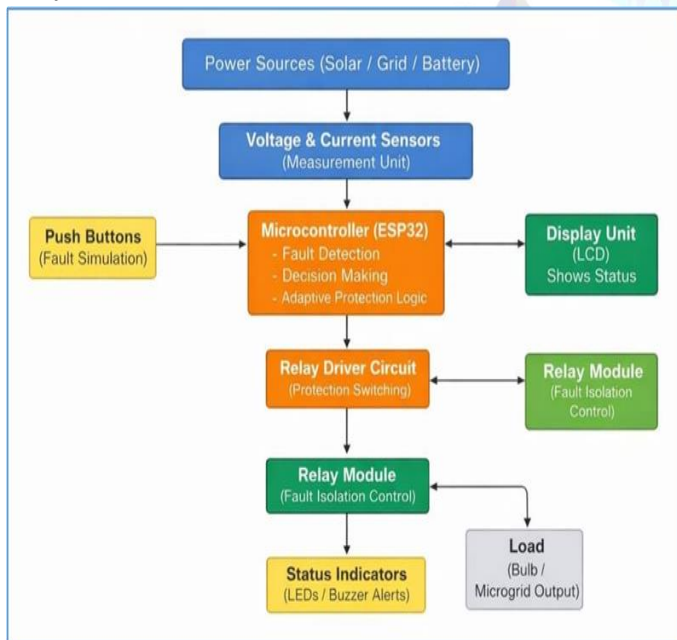


Fig. 1. Block Diagram of Adaptive Microgrid Protection System

The system architecture consists of multiple functional units including power sources, sensing units, control unit, protection unit, and user interface modules. The power sources include solar, wind, and grid supply,

which are connected to the load through relay modules. Voltage and current sensors continuously monitor electrical parameters and send real-time data to the ESP32 microcontroller. The controller processes these inputs and determines system conditions based on predefined adaptive logic. The integration of multiple sources ensures flexibility and reliability in power supply.

B. Operational Methodology

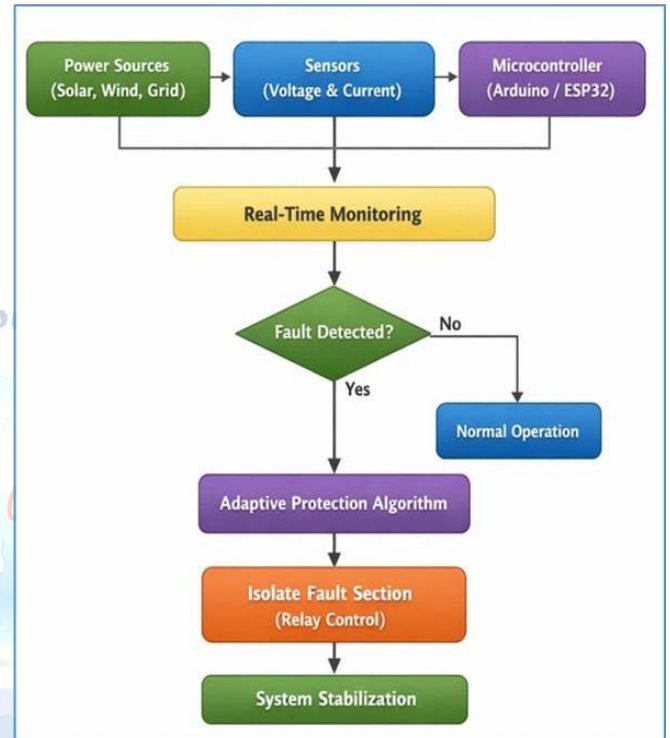


Fig. 2. Flowchart of Adaptive Microgrid Protection System

The system operates based on a continuous monitoring and decision-making process. Initially, the system measures voltage and current parameters from all connected sources. These values are compared with predefined threshold limits to determine system health. If all parameters remain within safe limits, the system continues normal operation. However, when abnormal conditions such as overcurrent, voltage drop, or source failure are detected, the system identifies the fault and initiates corrective actions.

The methodology follows a sequential process: sensing → data acquisition → condition analysis → fault detection → decision-making → relay actuation → system stabilization. This adaptive approach ensures rapid response and minimizes system disruption.

C. Circuit Implementation

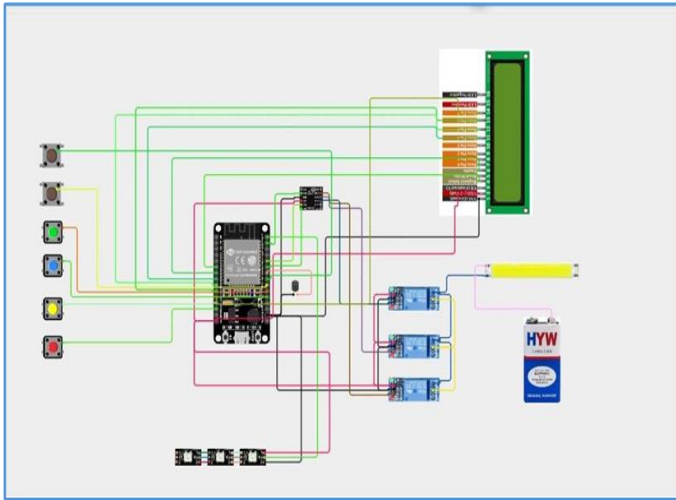


Fig. 3. Circuit Diagram of Adaptive Microgrid Protection System

The hardware implementation is based on an ESP32 microcontroller interfaced with relay modules, LCD display, push buttons, LEDs, and a buzzer. The push buttons are used to simulate different fault conditions such as phase faults and source faults. The LCD provides real-time system status, while LEDs and buzzer indicate fault conditions. Relay modules are used to switch between different power sources. The ESP32 processes input signals and controls the relays accordingly to isolate faulty sections and maintain continuous power supply.

D. Hardware Prototype and Implementation

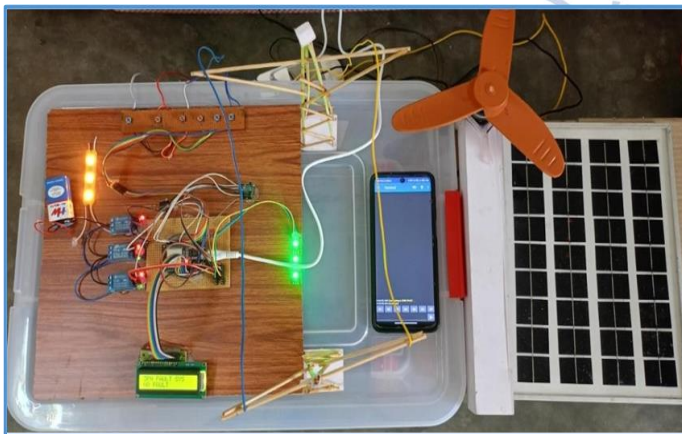


Fig. 4. Hardware Prototype of Adaptive Microgrid Protection System

The hardware prototype demonstrates the practical implementation of the proposed system. It includes ESP32, relay modules, power supply, LCD display, LEDs, buzzer, and interconnecting elements. The system

continuously monitors inputs and responds to simulated fault conditions using embedded control logic. Upon detection of a fault, the system isolates the faulty section and switches to an alternative source, ensuring uninterrupted operation.

E. Fault Detection and Adaptive Control Strategy

The core methodology is based on real-time fault detection using threshold-based logic. The system continuously compares measured parameters with predefined limits. If the current exceeds a threshold value or voltage drops below a safe level, a fault is detected. The system identifies different types of faults such as R-phase, Y-phase, B-phase faults, solar faults, wind faults, and total grid failure.

Once a fault is detected, the adaptive control strategy determines the appropriate action based on source availability. The microcontroller generates control signals to operate relay modules, disconnecting the faulty source and connecting a healthy alternative. This ensures selective fault isolation and continuous power supply.

F. Relay Switching Mechanism

The relay modules act as switching devices that connect or disconnect power sources based on system conditions. Under normal operation, the preferred source (typically the grid) supplies power to the load. When a fault occurs, the corresponding relay is deactivated, and another relay is activated to switch to a healthy source such as solar or wind. This fast switching mechanism minimizes power interruption and enhances system reliability.

G. Monitoring and Communication

The system includes real-time monitoring through LCD display, LED indicators, and buzzer alerts. Additionally, the ESP32 enables communication via Bluetooth or Wi-Fi, allowing remote monitoring using mobile devices. This feature enhances user awareness and aligns the system with modern smart grid technologies.

4. RESULTS AND DISCUSSION

A. System Performance under Normal Conditions

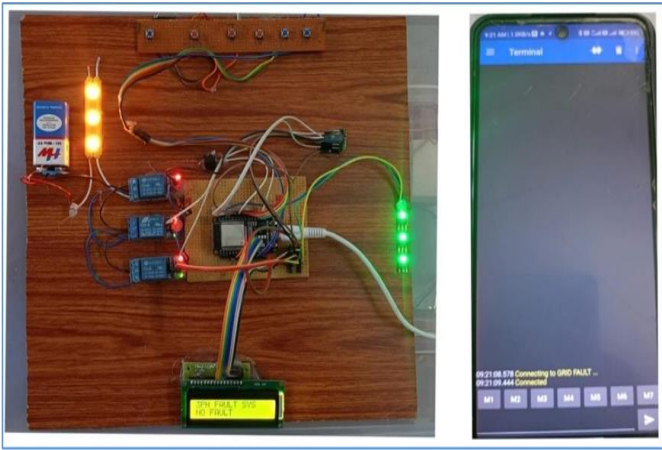


Fig. 5. System Operation under Normal Condition

Under normal operating conditions, the adaptive microgrid protection system maintains a stable and continuous power supply to the load without any interruption. The ESP32 microcontroller continuously monitors system parameters such as voltage and current from all available sources. Since no abnormal condition is detected, the system operates in its default configuration, where the primary power source (typically the utility grid) supplies power to the load.

During this condition, all relays remain in their default energized state, allowing uninterrupted power flow. The LCD display indicates "NO FAULT" or "SYSTEM NORMAL," confirming stable system operation. LED indicators (green) remain ON to represent healthy conditions, and the buzzer remains OFF, ensuring no unnecessary alerts. This demonstrates that the system effectively performs real-time monitoring without triggering false operations, thereby ensuring reliability and stability during normal conditions.

B. System Performance under Fault Conditions

The system was tested under various fault scenarios to evaluate its fault detection accuracy, response time, and adaptability. Faults were simulated using push buttons representing different conditions such as phase faults, source faults, and complete grid failure.

1) Phase Fault Analysis (R, Y, B Phases)

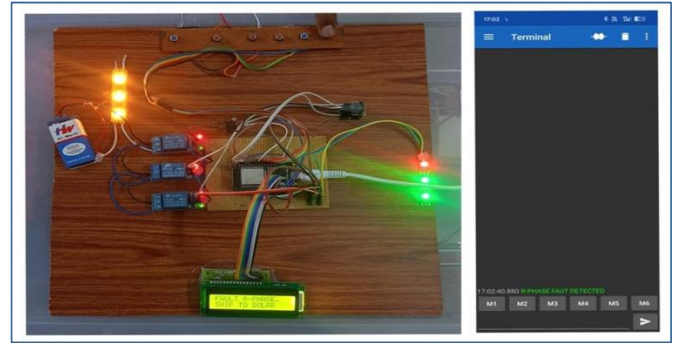


Fig. 6. Phase Fault Detection and Source Switching

When a phase fault (R, Y, or B) occurs, the system immediately detects the abnormal voltage condition using sensor inputs. The ESP32 processes this information and identifies the affected phase. Upon detection, the controller activates the relay mechanism to disconnect the faulty grid supply and automatically switches the load to an alternative source, typically the solar system.

The LCD displays messages such as "FAULT R-PHASE - SHIFT TO SOLAR," while the buzzer is activated to alert the user. LED indicators change status to visually represent the fault condition. This rapid response ensures that the fault is isolated quickly and power supply is maintained without interruption. The system demonstrates high reliability and selectivity in handling phase faults.

2) Solar Source Fault

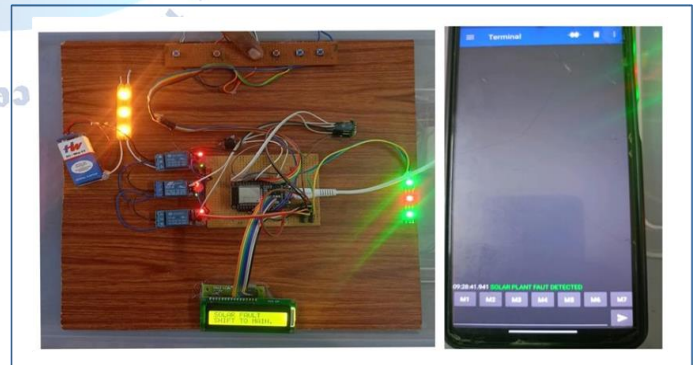


Fig. 7. Solar Source Fault Handling

In the event of a solar source failure, such as voltage drop or output interruption, the system detects the abnormal condition through sensor feedback. The ESP32 controller identifies the fault and isolates the solar source by deactivating the corresponding relay. Simultaneously, the load is transferred to the main grid supply.

The LCD displays “SOLAR FAULT – SHIFT TO MAIN,” and an audible alert is generated using the buzzer. This seamless transition ensures uninterrupted power supply and protects the system from instability caused by faulty renewable sources.

3) Wind Source Fault

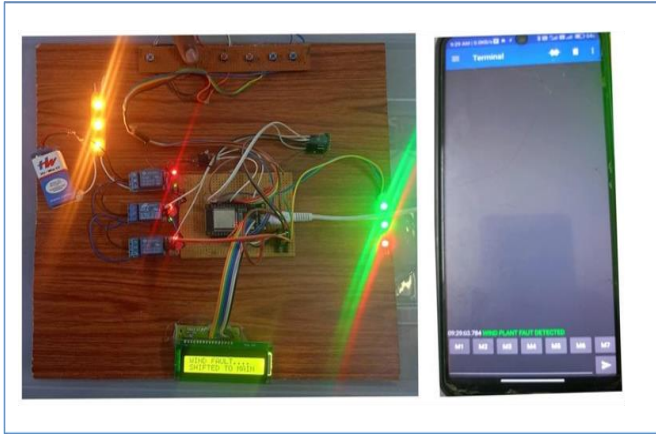


Fig. 8. Wind Source Fault Handling

Similarly, when a wind source fault occurs due to voltage fluctuations or supply interruption, the system detects the fault and isolates the wind source using relay control. The load is automatically shifted to the grid or another available source.

The LCD displays “WIND FAULT – SHIFT TO MAIN,” and LED indicators along with buzzer alerts notify the user. This demonstrates the system’s capability to handle renewable source failures efficiently while maintaining system continuity.

4) Complete Grid Failure

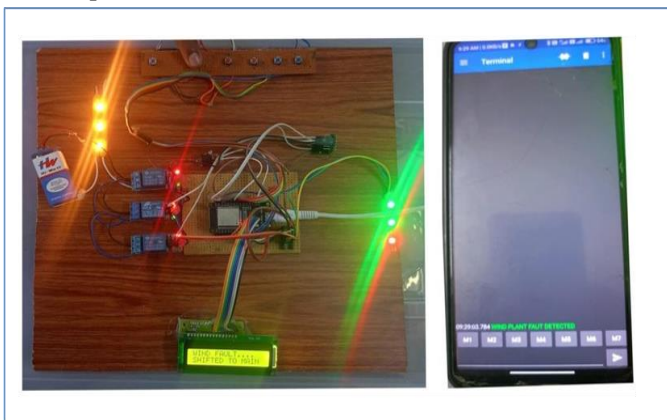


Fig. 9. Complete Grid Failure and Backup Operation

In the case of total grid failure, where all three phases are lost, the system detects the absence of voltage across all

phases. The ESP32 controller identifies this as a critical fault condition and isolates the grid supply completely.

The system then activates the solar backup source using relay switching to ensure uninterrupted power supply. The LCD displays “GRID FAILURE – SOLAR ACTIVE,” and the buzzer provides an alert. Once the grid supply is restored and stabilized, the system automatically reconnects to the grid, demonstrating self-healing capability.

5. CONCLUSIONS

The Adaptive Microgrid Protection System presented in this work provides an effective and reliable solution for protecting modern microgrids integrating renewable energy sources. The system successfully addresses the limitations of conventional protection methods by incorporating real-time monitoring, adaptive decision-making, and automatic fault isolation.

The implementation using an ESP32 microcontroller, relay modules, and sensing units enables accurate detection of various fault conditions, including phase faults, solar faults, wind faults, and complete grid failure. The system demonstrates the ability to isolate faulty sections and seamlessly switch to alternative power sources, ensuring uninterrupted power supply and enhanced system reliability. The inclusion of user interface features such as LCD display, LED indicators, and buzzer alerts further improves system usability and monitoring.

Experimental results confirm that the proposed system offers fast response, high reliability, and efficient operation under both normal and fault conditions. The adaptive control strategy enhances system stability and reduces downtime, making it suitable for real-world microgrid applications.

In conclusion, the proposed system provides a cost-effective, scalable, and intelligent protection solution for modern power systems. Future work can focus on integrating advanced technologies such as artificial intelligence for predictive fault analysis, IoT-based remote monitoring, and smart grid communication systems to further enhance system performance and automation.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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