

Developing IoT-based Smart Agent Systems for Real-Time Fault Detection and Reliability Enhancement in Microgrids

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Publication Date: 2026/06/18

Abstract: The contemporary surge in global energy consumption, driven by the proliferation of sophisticated industrial machinery and consumer electronics, has placed unprecedented strain on traditional power infrastructures. These escalating demand profiles, coupled with stochastic usage patterns and a deficiency in real-time telemetry, frequently necessitate load-shedding protocols to maintain grid integrity. This paper introduces an Internet of Things (IoT)-integrated Smart Multifunctional Agent (SMA) designed for the autonomous monitoring and protection of hybrid Microgrids. The proposed system leverages a high-precision sensor suite to monitor critical parameters, including voltage, current, and active power, while utilizing an Arduino-NodeMCU architecture for real-time data acquisition. Unlike conventional monitoring frameworks, the SMA incorporates intelligent logic to execute proactive safeguards against overcurrent and undervoltage anomalies via automated relay actuation. In alignment with Smart City digitalization trends, the architecture employs a Wi-Fi-enabled telemetry link to transmit energy metrics to a cloud-based dashboard. This interface provides users with platform-agnostic visibility into their power consumption through unique channel identifiers. Experimental results demonstrate that the integrated Smart Agent facilitates rapid fault localization and autonomous system normalization, significantly reducing downtime and enhancing the operational efficiency of localized distribution networks.

How to Cite: Ekaba S. O.; Ofualagba G.; Uzedhe G. O. (2026) Developing IoT-based Smart Agent Systems for Real-Time Fault Detection and Reliability Enhancement in Microgrids. *International Journal of Innovative Science and Research Technology*, 11(6), 551-559. <https://doi.org/10.38124/ijisrt/26jun493>

I. INTRODUCTION

To prevent people and property from damage or injury, electrical faults in a power system must be cleared fast. In the early days of electrical power systems, the fault clearing was administered by the maintenance staff, who visually detected the fault and manually operated a switch to clear the fault. As fault currents became larger and the operating requirements of the electric power system became more stringent, the need for automatic fault clearance became a necessity. In the early days of automatic fault clearing, a fault was detected by electromechanical relays (Khalid M, 2024). The measured quantity, such as a voltage or a current, was transformed to a mechanical force which operated the relay when a preset threshold was exceeded. Following the advent of electronics such as transistors and operational amplifiers, solid-state relays were developed. The characteristic of such relays were implemented by circuit design. The rising demand for energy, driven by the expansion of industries, shopping malls, and everyday household gadgets, has sparked an urgent call for innovative energy solutions (Abdullahi & Hassan, 2022). Some of the main hurdles we face include the tricky task of integrating renewable energy sources, ensuring grid flexibility and security, gaining user acceptance, and

addressing the gaps in standards and protocols necessary for the effective implementation of smart grids (Medina et al., 2023). Keeping the grid stable and safe becomes especially challenging with the growing use of distributed energy resources (Tian et al., 2023). One major concern is safeguarding microgrids at their Point of Interconnection (POI) with the main utility grid, particularly from single-line-to-ground (SLG) faults that can happen on the interconnection lines (Jayaprakash et al.,). Conventional power distribution architectures, historically characterized by inherent operational inefficiencies and rigid control frameworks, are undergoing a fundamental paradigm shift. The integration of Internet of Things (IoT) technologies is facilitating this transition, converting legacy grids into decentralized, high-fidelity systems capable of adaptive energy management and real-time responsiveness [10]. The deployment of IoT-enabled infrastructures facilitates superior monitoring and adaptive control, which are vital for the incorporation of Renewable Energy Resources (RERs). While the integration of these resources is a cornerstone of the Smart Grid (SG) evolution, it presents substantial operational hurdles. These include the synchronization of intermittent power sources with the legacy grid and the management of bidirectional power flows, necessitating the

use of advanced control agents to ensure system resilience. This integration presents several challenges (Pradeep et al., 2024). Protection of microgrids at the Point of Interconnection (POI), specifically focusing on the challenges of detecting single-line-to-ground (SLG) faults on interconnection lines when the microgrid is ungrounded (Joha et al., 2022). To protect both domestic and institutional infrastructure, this research highlights the need for a comprehensive control system that addresses risks like overheating, overcurrent, and fire hazards. The suggested design focuses on two main goals: enhancing energy efficiency through smart-load management while ensuring a user-friendly control environment. By separating system reliability from strict Wi-Fi network requirements, this architecture guarantees strong performance even in areas with unreliable communication infrastructure (Reddy et al., 2020). The pursuit of efficient power distribution is increasingly dependent on the deployment of intelligent architectures. By leveraging IoT-based monitoring at the substation level, as advocated by Rao et al. (2023), systems can achieve superior fault isolation and service restoration. According to Rao et al. (2024), the dual objectives of maximizing service continuity and minimizing actual power losses are essential benchmarks for a functional distribution network. Furthermore, achieving an optimal radial configuration remains a significant challenge; however, as noted by Varela-Aldás (2022), effective reconfiguration is necessary to optimize power flow while ensuring the system remains within safe voltage stability margins.

➤ *An IoT-Based Automated Monitoring and Protection System is Implemented in this Work:*

- In smart grids, current and voltage sensors are used to continually monitor electrical characteristics (voltage, current, and power usage).
- To send measured data in real time to a web server or mobile application via a Wi-Fi module, allowing users to view energy usage information remotely.
- Automatically detect fault conditions (overload, overvoltage, and undervoltage) and isolate problematic grid portions with protective relays to ensure safety and reliability.
- To provide users with analytics and visualization tools for efficient energy management and consumption tracking.
- To improve communication between utility companies and customers to deliver better service and save more energy.

II. LITERATURE REVIEW

A variety of frameworks for smart home and asset automation have emerged in recent scholarly discourse.

Shende et al. (2019) introduced a specialized monitoring system for electrical assets designed to respond autonomously to anomalous operating conditions. Central to this architecture is a command processor that leverages sensory data to execute fault localization and diagnostic responses. This signifies a broader shift in distribution

network management; while legacy systems suffered from sparse telemetry and restricted real-time visibility, modern infrastructure including transformers, circuit breakers, and power lines is increasingly outfitted with integrated monitoring devices. This evolution effectively surmounts the constraints of conventional supervision, enabling the granular, real-time data acquisition necessary for sophisticated grid control.

Ganney et al. use of IEDs as controllers based on voltage and current sensors, fault indicators, the utilization of SCADA technologies, the development of automatic meter reading technology, and high-speed communication technologies enables fast and accurate responses to fault situations, with real-time monitoring features. The use of hybrid computational intelligence like merging fuzzy logic with wavelet transforms has shown to be quite effective in accurately classifying transient anomalies. However, it's important to note that these advancements mainly act as diagnostic tools. There's still a significant gap when it comes to the post-fault normalization process, as the current models don't offer a clear strategy for getting the distribution system back to its optimal operating state after a fault has been isolated.

Uddin et al. carried out an in-depth evaluation of microgrid (MG) architectures, focusing particularly on the control strategies and technical challenges that come with their implementation. Their analysis highlighted essential operational needs, such as energy management, the integration of fluctuating renewable sources, and overall system stability. By looking into specific factors like grid flexibility, hierarchical load balancing, and optimizing energy storage, the study emphasized the key elements that determine the reliability of microgrids. However, the authors pointed out some major systemic hurdles, including insufficient communication infrastructures, high capital costs, and a lack of unified regulatory frameworks. These insights led to recommendations for future research paths that focus on advanced control intelligence and the integration of electric vehicles (EVs).

Bhat et al. (2017) came up with an innovative IoT-based framework aimed at seamlessly managing home energy use while also keeping an eye on environmental safety. This setup employs a standard web server along with a Wi-Fi-enabled microcontroller (ESP8266) to enable wireless monitoring and control of various devices, such as indoor and outdoor lights, power outlets, and ventilation systems. But it doesn't stop there; the prototype also includes a suite of sensors for tracking temperature, humidity, and smoke, giving users real-time insights into their environment. One of the standout features of this system is its ability to work across different platforms, thanks to a web-based dashboard that makes it easy to access from various devices, as long as you have an internet connection.

Khalid et al., (2024). developed a method for integrating renewable energy sources (RES) into smart grids, concentrating on improving grid flexibility and reliability while addressing issues like RES unpredictability and a lack

of inertia support. The report underlines the need for improved monitoring and communication networks to support renewable integration. However, the study identifies inadequacies in addressing the complexities of system design, operation, and resilience, notably in dealing with uncertainties related to renewable energy output and grid stability.

III. METHODOLOGY

The traditional way of managing power grids can lead to a 'cascading' outage effect. This happens because, without a smart decision-making system, healthy parts of the grid stay

offline while we investigate faults. Right now, we depend on feedback from downstream systems and old circuit breaker statuses, which just isn't as accurate as the data we could get from IoT technology. If you look at the conventional outage management timeline in Figure 1, you'll see that the manual process of identifying and fixing issues can take over an hour. To tackle this problem, this study suggests using a decentralized Smart Agent system. By swapping out manual reporting for smart, quick fault-detection algorithms, this agent can send out commands to restore power to healthy areas almost instantly, cutting down the usual 45-to-75-minute wait that comes with traditional methods.

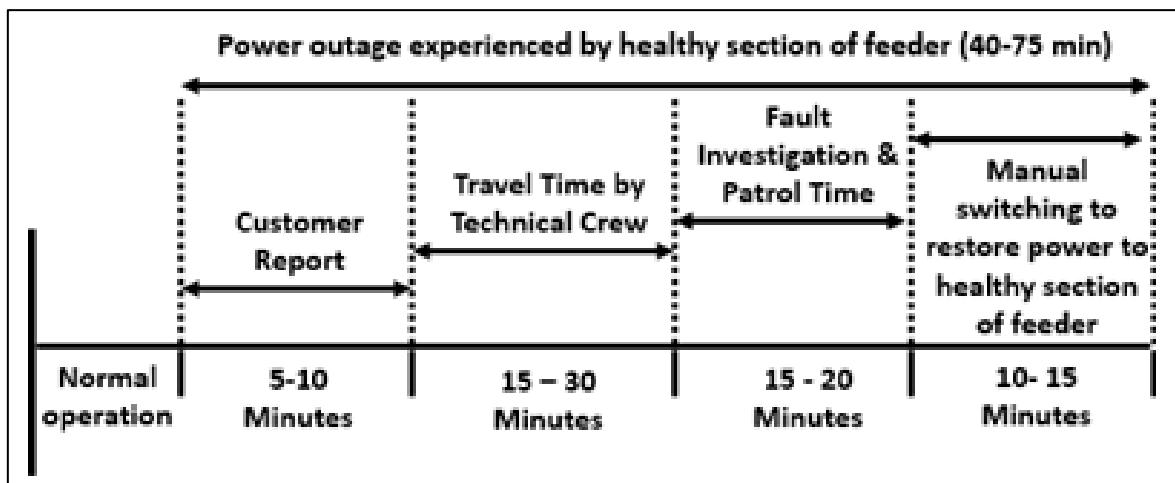


Fig 1 Convectional Outage Management Procedures

Revamping the efficiency of old distribution networks requires a shift from simply reacting to problems to proactively managing contingencies. With autonomous monitoring systems in place, we can significantly cut down the Mean Time to Repair (MTTR) by pinpointing faults without needing human input. When these systems are paired with the ability to operate field switchgear remotely, we can avoid the need for physical dispatch to the fault site, enabling almost immediate network reconfiguration. The suggested framework focuses on a dual-purpose design—intelligent fault monitoring and remote actuation—fully connected

through IoT protocols. This combination not only enhances situational awareness but also allows the smart agent to quickly implement restoration procedures for the healthy parts of the feeder with minimal delay. The performance of the system is shown in Figure 2. The time shown in Figure 2. The time taken for supply restoration to the healthy section of the feeder can be shortened to less than 5 min after the implementation of such a system. The deployment of such a system is expected to improve the SAIFI and SAIDI indices significantly due to the shortened time for fault localization and normalizing of the system.

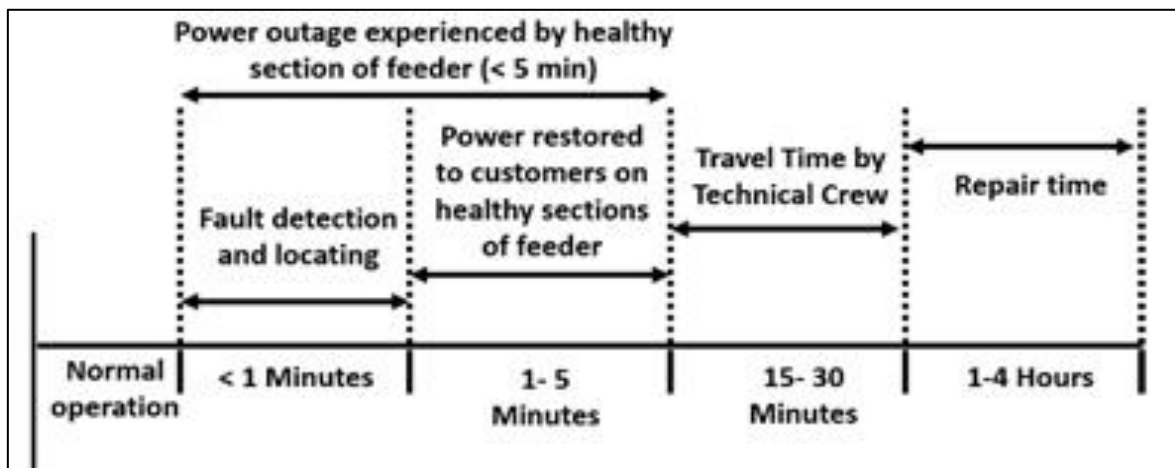


Fig 2 With Smart Fault Detection and Remote Control

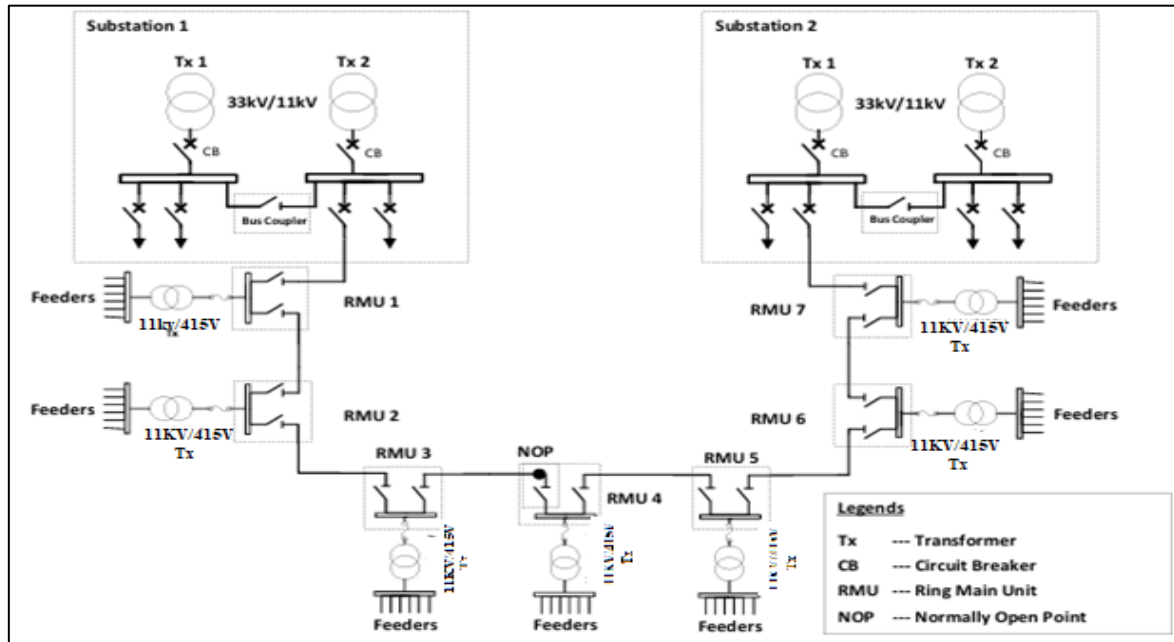


Fig 3 33/11 kV Substation System at Asaba.

IV. PROPOSED METHOD

The smart grid framework we're proposing leverages SMART agent Technology and IoT to enable autonomous power management and real-time, high-precision fault detection. The proposed system architecture features a distributed hardware setup that revolves around an Arduino microcontroller, which is connected to a NodeMCU module equipped with an ESP8266 Wi-Fi unit, along with a specialized sensor array. The Arduino takes care of local signal acquisition and conditioning, while the NodeMCU acts as a SMART agent node, handling data preprocessing, making local decisions, and managing wireless communication. This setup allows for the continuous gathering of essential data like voltage, current, and real power measurements offering detailed insights into the performance of the microgrid. The SMART agent nodes send the processed data streams to a cloud server and a mobile interface in real time, enabling remote monitoring, automated fault detection, and supervisory control. By integrating SMART agent logic at the edge, the system embraces a data-driven approach that minimizes response time to any anomalies. This architecture boosts microgrid reliability by providing immediate access to current operational metrics and allows for proactive measures before small issues turn into major system failures.

➤ System Components

- Voltage Sensor (ZMPT101B): The voltage sensor is used to capture voltage readings from the electrical grid for monitoring and analysis.
- Current Sensor (ACS712): The system monitors current flow throughout
- NodeMCU (ESP8266): Transmits data to the IoT platform in real time via the Wi-Fi module.
- Arduino Microcontroller: The Arduino Microcontroller is the system's central component, responsible for

connecting with sensors, processing data, and relaying it via Wi-Fi.

- Relay Module: It auto-disconnects the load when overvoltage or undervoltage conditions occur.
- Buzzer Module: Provides audible alerts in the event of a failure.

➤ Fault Simulation and Monitoring

Wireless communication between the Arduino and the web interface is made possible with the ESP8266 Wi-Fi module that's built into the NodeMCU. To set up serial communication, we connect the Arduino Uno and NodeMCU using digital pins 2 and 3, which allows for a smooth two-way data exchange. We gather real-time electrical parameters—like voltage, current, and power—using the ZMPT101B voltage sensor and the ACS712 current sensor, which send the data to the Arduino for processing. After the Arduino processes this information, it sends the results to the NodeMCU, which then uses AT commands to relay the data to the web interface. This web interface acts as the user dashboard for the system and can be hosted either locally or on a remote server. It shows live sensor readings and offers control options for managing the system from afar. The ESP8266 keeps the webpage updated with the latest voltage, current, and power values, along with fault alerts for issues like overvoltage, undervoltage, and overload, all generated by the Arduino. Depending on these conditions, the Arduino can take control actions, such as turning on a relay or sounding a buzzer. The NodeMCU then shares this information with the webpage, enabling users to monitor and manage the system remotely through the interface.

➤ Interface Design and Access Control

Relay state and fault alert signals serve as system inputs, while the NodeMCU functions as an IoT gateway to transmit telemetry data to the cloud and receive control commands from it. Data exchange between the IoT device and the cloud is managed through an IoT Hub platform. For monitoring and

control, the system employs a web-based interface accessible from any computer or mobile device via a standard web browser. The webpage is hosted either on the NodeMCU ESP8266 module itself or on a remote server, and can be accessed by entering the corresponding IP address or URL. Users require only an internet connection and a browser such as Chrome or Firefox to view real-time parameters including voltage, current, and power and to manage system operations. Because the interface is web-based, no additional software or mobile application installation is needed.

➤ *Operational Thresholds in Fault Simulation*

The threshold values for overvoltage (240 V), overload (100 W), and undervoltage (120 V) were selected primarily for demonstration purposes. They are intended to illustrate how fault conditions arise and how the system responds under abnormal operating scenarios. These values function as example limits to showcase the fault detection process within the IoT-based smart grid monitoring system, rather than being based on specific application requirements. By applying these predefined limits, the system’s capability to detect and respond to deviations from normal operating conditions can be clearly demonstrated. It should be noted that these thresholds are adjustable and can be reconfigured to suit the operational environment, load characteristics, and device specifications of a real-world deployment.

➤ *Fault Detection and Protection*

When the Smart Agent detects abnormal conditions such as overload, undervoltage, or overvoltage, it initiates an autonomous response by actuating the relay module to isolate the load from the grid, thereby preventing potential damage. Simultaneously, the agent triggers a buzzer to provide an audible fault alert, informing the user of the specific anomaly and enabling timely intervention. This dual-layer response combining automated load disconnection with real-time fault

notification enhances situational awareness and strengthens system safety by mitigating the risk of electrical damage as it occurs.

Figure 4 illustrates an IoT-based SMART Agent system designed for real-time monitoring and autonomous protection in smart grid applications. The architecture integrates multiple electronic components to continuously acquire and regulate key electrical parameters, primarily voltage and current. The SMART Agent processes this sensor data locally to make autonomous control decisions, while also transmitting telemetry to an IoT web server for remote monitoring, access, and supervisory control. By combining embedded sensing, decision-making, and communication, the system delivers both autonomous on-device protection and cloud-enabled oversight. The overall framework comprises coordinated hardware and software modules that enable intelligent, real-time grid management. The software utilizes current and voltage sensors to track the power usage of household appliances and control systems, alerting users if any parameters going out of range. The setup features an Arduino UNO, a Node MCU ESP8266 Wi-Fi Module, a ZMPT101B voltage sensor, and ACS712-20 current sensor modules. The Arduino UNO acts as a microcontroller, enabling you to program custom code to run whenever needed. It is also a very capable microcontroller that can receive and send data over the Internet using a variety of modules and shield platforms. The results are showcased through an IoT solution that can be accessed via a website or mobile app. For instance, Android-based IoT monitoring can display important metrics like voltage, current, and power usage. Meanwhile, a web or mobile application not only visualizes this data but also sets off alarms when needed. Both web and mobile systems calculate energy usage data for power consumption, offering detailed insights into electrical values such as voltage, current, power, and energy.

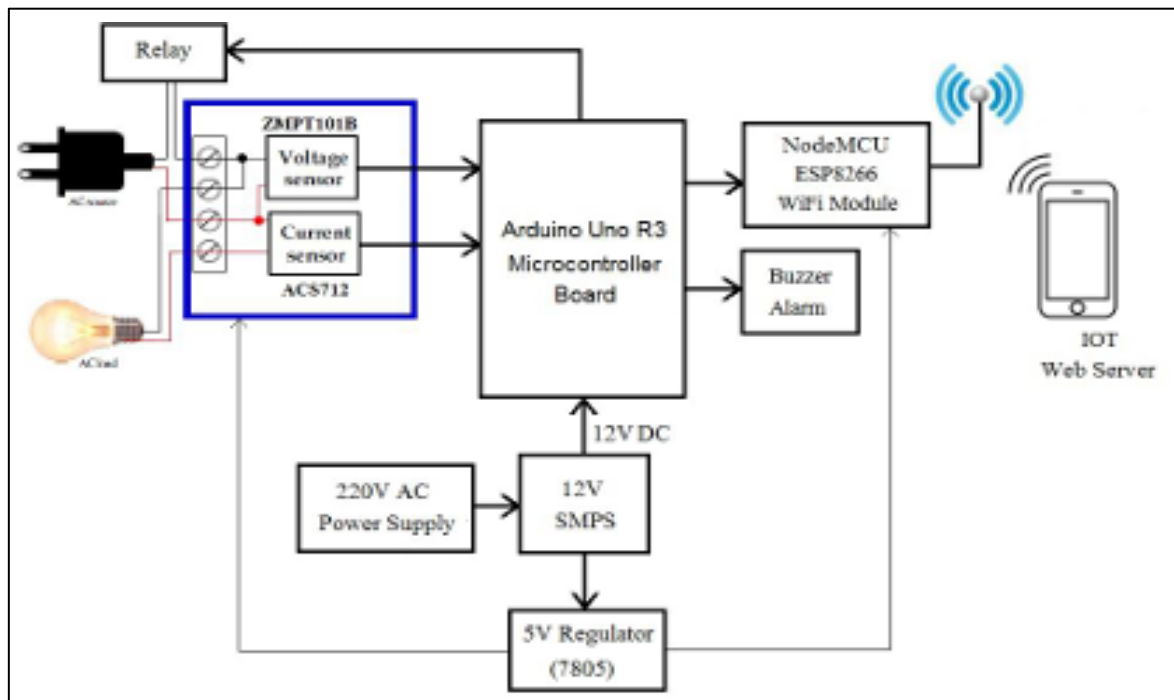


Fig 4 Shows the Proposed System Architecture.

V. RESULTS AND DISCUSSION

The Smart Agent-based fault monitoring and normalization system was evaluated in two operational modes: one under normal conditions to verify baseline functionality, and another with simulated faults on the 11 kV line to assess the agent’s fault detection and response behavior.

➤ Normal System Operation

The system’s electrical behavior is modeled and simulated using ETAP software to ensure accurate performance analysis. when everything is running smoothly, all the red LEDs should be off, showing no signs of any issues. Meanwhile, all the DPDT relays are in the “closed” position, except for the normally open point (NOP- DPDT Relay 7). Moreover, all seven LED bulbs (Loads) light up as usual. The smart fault monitoring interface is accessed through a web browser, with entry restricted to authorized users only. After successfully signing in, we noticed that the current configuration of the distribution system was updated and modeled in real-time on the fault monitoring website. The “updated on” field provides the date and time information of the system modeling and is refreshed every two to four seconds, depending on the upload speed. Moreover, the green color lines indicate that the lines are energized and that the current system is in a “healthy” mode, as implied in the “remarks.

➤ Simulating Fault on Line 11

The resilience of the protection scheme was put to the test with a simulated fault on Line 11. The results from the experiment clearly show that the system was able to pinpoint the fault accurately, providing visual feedback through the Line 11 status LED. To protect the system, the power supply to the load cluster specifically LEDs 4 through 7 was quickly cut off before reaching the NOP interface. This swift action helps stop the fault from spreading across the sub-grid, highlighting how effective the smart monitoring unit is in keeping the grid's integrity intact, as illustrated in Figure 5.

When a Fault is detected on Line 11, the protection logic kicks in and sends a trip command to Circuit Breaker 2 (DPDTS2). This action helps protect the upstream network by shutting down LEDs 4, 5, 6, and 7. At the same time, this event is synced with the digital twin model on the smart fault monitoring website, which gives a real-time status update. One of the standout features of the interface is the automatic diagnostic feedback, which suggests 'opening' Switchgears 9 and 11 to isolate the fault locally. Additionally, there's an email alert system that prompts immediate action from the administration. The workflow for restoration and isolation wraps up through a remote-control interface; after a thorough authentication process, the operator sends control commands for Switchgears 9 and 11, which the server then processes for real-time action in the field.

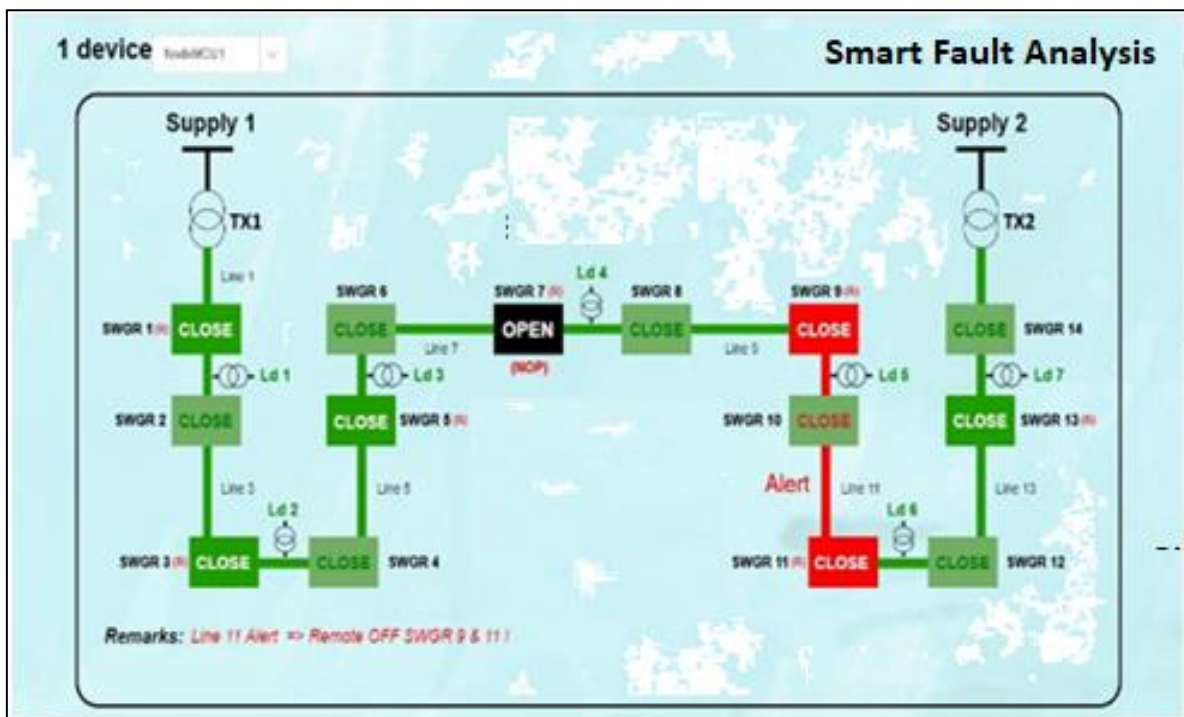


Fig 5 Smart Online Fault Monitoring System Indicating a Fault on Line 11

The seamless connection between the cyber and physical layers is confirmed when the server uses direct methods based on the control vectors it receives. To ensure that this remote actuation is reliable, there's an acknowledgment-based feedback loop in place; the IoT device verifies that the command has been executed before

the server refreshes the web dashboard. You can see this entire control process illustrated in Figure 6, which depicts the low-latency communication path. Figure 7 provides a clear example of the system's output after the command is sent, showcasing the real-time status updates that facilitate verified remote grid reconfiguration.

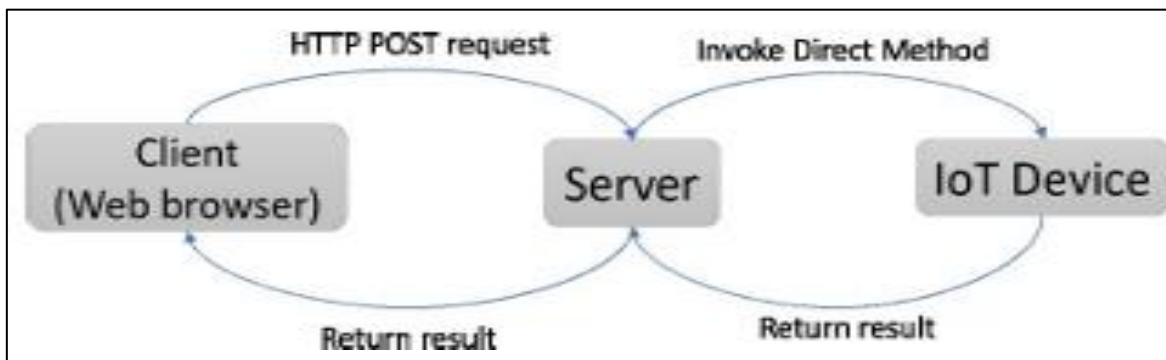


Fig 6 Communication Between Client and IoT Device



Fig 7 Sample Output from the Remote-Control Web after a Control Command is Sent.

Following the successful isolation of the fault, a restoration protocol was executed to re-energize the non-faulty segments of the feeder, specifically targeting Load 4 (LED 4). By remotely 'closing' Switchgear 7, which serves as the Normally Open Point (NOP), the system effectively facilitated a tie-line transfer, sourcing power from the adjacent Supply Source 1 (Transformer 1). Simultaneously, the remote actuation of Circuit Breaker 2 (DPDTS2) restored the supply trajectory for Loads 6 and 7.

Table 1 presents a representative telemetry dataset from the IoT-based monitoring unit, capturing real-time variations in voltage, current, and active power. The system's control logic continuously evaluates these parameters against predefined thresholds to ensure operational safety; upon detecting anomalies such as overvoltage or overcurrent, the agent initiates automated mitigation protocols, including alarm triggering and circuit interruption. Each entry in Table 1 demonstrates the system's precision in telemetry acquisition and its capacity for rapid, autonomous contingency management.

• Identify the Following Fault Scenarios:

- ✓ Overvoltage: A voltage that exceeds a preset threshold (for example, >230V).
- ✓ Overcurrent: The current exceeds safe limits.
- ✓ Overload: Power usage exceeds the rated capacity of 100w.

Table 1 clearly shows how effective the IoT-integrated monitoring framework is at keeping the grid reliable and safe. With its precise telemetry for voltage, current, and active power, the system can quickly spot any unexpected irregularities, helping to prevent potential cascade failures. Thanks to automated fault detection algorithms, it catches anomalies right at the start, which greatly reduces the risk of asset damage and shortens service interruptions.

Automated solutions that swiftly isolate issues, such as rerouting power or cutting off portions of the grid, improve safety. Furthermore, the system's capacity to control renewable energy sources and optimize power distribution enhances grid stability overall and lowers the possibility of overloads or blackouts, which helps to provide customers with safer, more dependable energy supply.

Table 1 Smart Grid Output: Voltage, Current, Power, Faults, and Trip Status

Voltage	Current(A)	Power (w)	Fault	Trip
226.6	0.28	63.09	Nil	No trip
221.66	0.46	101.02	Overload	Trip
54.65	0.09	4.92	Under Voltage	Trip
240.12	0.50	120.05	Overload	Trip
255.3	0.55	140.4	Overvoltage	Trip

➤ *SMART Agent-Enabled Grid Monitoring & Protection*

The SMART Agent system integrates high-precision sensors with an Arduino microcontroller and a NodeMCU ESP8266 Wi-Fi module to acquire, process, and transmit grid data to an IoT platform. This enables remote, real-time monitoring of grid parameters from any mobile device or computer, allowing continuous oversight and rapid response to emerging issues. With its intuitive interface, remote accessibility, and autonomous protective functions, the agent-based system provides a practical solution for enhancing grid resilience, efficiency, and sustainability under modern energy demands.

The SMART Agent continuously monitors voltage and current with high accuracy, enabling precise power consumption analysis across diverse loads. During operation, the agent autonomously identifies abnormal conditions such as overvoltage, undervoltage, and overload. Upon detecting a fault, it independently actuates a relay-based safety circuit to isolate the affected load from the grid. This autonomous diagnosis and isolation prevent potential electrical failures, demonstrating the agent’s capability to improve grid dependability and safety. By enabling real-time fault detection and response, the system sustains operational continuity while minimizing the risk of equipment damage and extended outages, confirming its effectiveness in strengthening grid reliability and protective measures.



Fig 8 Voltage, Current, Power Parameters are Monitored in Real Time on the Webpage.

➤ *Operational Performance Analysis*

To evaluate the operational performance of the SMART Agent, the system was restarted and executed multiple times to collect timing data. Two timing metrics were recorded: the timestamp at which data was acquired by the IoT device, referred to as read time, and the timestamp at which the data was received by the web server, referred to as web time. For each run, the agent processed 6 data samples, with each sample containing a corresponding read time and web time pair. To improve measurement accuracy, two independent data sets were collected. Table 2 presents the analysis of read time and web time across these sets. The read time was derived from the timestamp, converted to local time, and

recorded using the last two digits for consistency. The web time was obtained from the “Queue Time” in app during data retrieval from the IoT Hub event. Analysis of the datasets revealed consistently longer initial read intervals of 33s and 26 s, respectively. This delay occurs because the SMART Agent undergoes an initialization phase, during which it establishes the necessary queries and network connections before transmitting the first set of data to the IoT Hub. The corresponding read intervals for each data varied between two and three intervals. The delay between the web time and read time for each dataset was calculated, and the average delays for each set of data were 1.12, 1.03, and 1.30 s, respectively.

Table 2 End-to-End Timing Performance of the SMART Agent

No	Timestamp	Read Time(s)	Web Time(s)	Read Interval(s)
1	1585916707	7	31.570	
2	1585916740	40	40.758	33
3	1585916742	42	43.05	2
4	1585916744	44	45.504	2
5	1585916747	47	47.776	3
6	1585916749	49	1.331	3

No	Timestamp	Read Time(s)	Web Time(s)	Read Interval(s)
1	1585915650	30	44.524	
2	1585915766	46	47.823	26
3	1585915768	49	50.061	3
4	1585915770	51	52.621	2
5	1585917773	53	55.234	2
6	1585917773	56	57.501	3

VI. CONCLUSIONS AND FUTURE SCOPE OF WORK

This Agent based IoT-enabled energy monitoring systems provide real-time tracking of key grid parameters such as voltage, current, and power consumption enhancing both operational efficiency and security. By leveraging Wi-Fi connectivity, these devices support remote access, automated data collection, and early fault detection, thereby improving system resilience and reducing energy losses. Conventional approaches to managing power outages in distribution networks are often labour-intensive and time-consuming, primarily due to the absence of automated fault monitoring and normalization in secondary distribution systems. The proposed SMART Agent system, implemented on the ETAP platform, addresses this limitation by enabling rapid fault detection, isolation, and service restoration. As a result, the response time was reduced from approximately 1 hour to under 5 minutes, as summarized in Table 2.

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