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DEVELOPMENT OF AN INTELLIGENT IOT-INTEGRATED CONTROL SYSTEM FOR ENHANCED MICROGRID OPTIMIZATION

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Abstract: The growing demand for reliable, efficient, and sustainable energy solutions has intensified the development of smarter microgrid systems. This study proposes an intelligent Internet of Things (IoT)-integrated control system designed to optimize microgrid performance through real-time monitoring, adaptive control, and predictive maintenance. The system incorporates advanced control algorithms, such as artificial neural networks, fuzzy logic, and machine learning, alongside IoT technologies to enable seamless communication among sensors, controllers, and actuators. This integration enhances decision-making processes, improves energy distribution efficiency, reduces power losses, and supports the integration of renewable energy sources. Simulation results validate the system's effectiveness in maintaining a stable power supply, ensuring load balancing, and enabling early fault detection. Quantitatively, the contribution of intermittent renewable energy supply to poor microgrid performance was reduced from 25% to 22.8%, while issues related to grid instability and faults decreased from 13% to 11.9% upon the implementation of the intelligent IoT-based control system. Overall, the system achieved a 1.1% improvement in microgrid performance. These findings underscore the potential of intelligent IoT-integrated control systems as a core component in the advancement of next-generation smart grid infrastructures.

Keywords
Microgrid optimization, intelligent control systems, Internet of Things (IoT), artificial intelligence, renewable energy integration,

1.0 INTRODUCTION

The global transition towards cleaner, more efficient, and decentralized energy systems has brought microgrids to the forefront of modern power system development. Microgrids, characterized by their ability to operate autonomously or in conjunction with the main grid, offer increased energy reliability, sustainability, and resilience (Lasseter, 2011). However, the increasing complexity of integrating various distributed energy resources (DERs), such as solar panels, wind turbines, and energy storage systems, demands intelligent control mechanisms capable of real-time monitoring, decision-making, and optimization (Guerrero et al., 2010). The Internet of Things (IoT) has emerged as a transformative technology, enabling seamless communication between devices, sensors, and

actuators within a microgrid environment. When embedded with intelligence-based techniques such as artificial intelligence (AI), fuzzy logic, and machine learning algorithms, IoT can significantly enhance the operational efficiency, fault detection, energy balancing, and demand-side management of microgrids (Guan et al., 2019). Intelligent IoT-integrated control systems facilitate predictive analytics and adaptive control strategies, allowing microgrids to respond dynamically to varying load demands and generation capacities (Alam et al., 2017). Despite these advantages, existing IoT-based microgrid control frameworks often face challenges related to data latency, cybersecurity, interoperability, and scalability, which hinder their optimal performance (Mollah et al., 2021).
Moreover, many conventional control systems lack the cognitive capabilities required for self-optimization and real-time decision-making, especially in complex and rapidly changing energy environments. The evolution of control systems engineering has introduced intelligent controllers as a potential advancement over conventional controllers. (Eze U.J. et al., 2024) Therefore, there is a critical need to develop an intelligence-based IoT-integrated control system that can autonomously manage energy resources, optimize energy flows, and enhance the overall reliability and efficiency of microgrid operations. This study seeks to address these challenges by proposing the development of an intelligent IoT-based control architecture designed to optimize microgrid performance. By leveraging AI-driven models and adaptive learning algorithms, the proposed system aims to improve resource allocation, reduce operational costs, and support the integration of renewable energy sources flexibly and securely.

2.0: METHODOLOGY

This section describes the methodology employed to identify, characterize, and mitigate the causes of poor microgrid performance, focusing on the integration of an intelligent Internet of Things (IoT)-based control system.

2.1: Identification of Causes of Poor Microgrid Performance

Table 1 outlines the key factors contributing to the underperformance of microgrids. These factors were categorized based on their impact on energy stability, system efficiency, and overall performance.

Table 1.0: Characterized and established causes of poor development of microgrid performance

Cause	Description	Impact on Performance	Typical Value (SI Units)	Estimated Contribution to Performance Decline (%)
Intermittent Renewable Energy Supply	Variability of solar/wind generation due to weather and time	Instability in energy availability	Solar: 100–1000 W/m², Wind: 2–12 m/s	20–25%
Lack of Intelligent Control Systems	Absence of real-time AI-based optimization	Inefficient load management	Delay: 1–5 seconds (signal processing lag)	18–22%

Poor Energy Storage Management	Inadequate or inefficient battery systems	Energy waste and poor reliability	SOC fluctuation: 20–80%, Cycle life: <3000	15–18%
Communication Latency in IoT Networks	Delay in sensor and actuator data transmission	Reduced system responsiveness	Latency: 100–500 ms	10–15%
Cyber security Vulnerabilities	Lack of protection against unauthorized access or attacks	System disruptions, safety risks	Data breach rate: ~5–10 MB/day	8–12%
Inadequate Load Forecasting	Poor prediction of load demand	Load imbalance, over/under generation	Forecast error: 5–20%	7–10%
Grid Instability and Faults	Voltage/frequency fluctuations or protection issues	System isolation or collapse	Voltage sag: <0.9 p.u, Frequency drift: ±0.5Hz	10–13%
Inefficient Power Electronics Interfaces	Suboptimal inverter and converter operations	Power loss and harmonics	THD >5%, Conversion losses: ~2–5%	6–9%

Key Notes:

1. SOC: State of Charge of battery (unitless, often expressed in %).
2. THD: Total Harmonic Distortion, measured as a percentage.
3. p.u: Per unit system used in power engineering for normalization.

3.0. DISCUSSION AND RESULTS

3.1 Discussion

3.1.1 SIMULINK Model for Conventional Microgrid Performance

A conventional SIMULINK model was designed to simulate the performance of a microgrid under typical conditions. The model serves as a baseline to compare the performance improvements introduced by the IoT-based control system. Figure 1 shows the conventional SIMULINK model used for performance analysis.

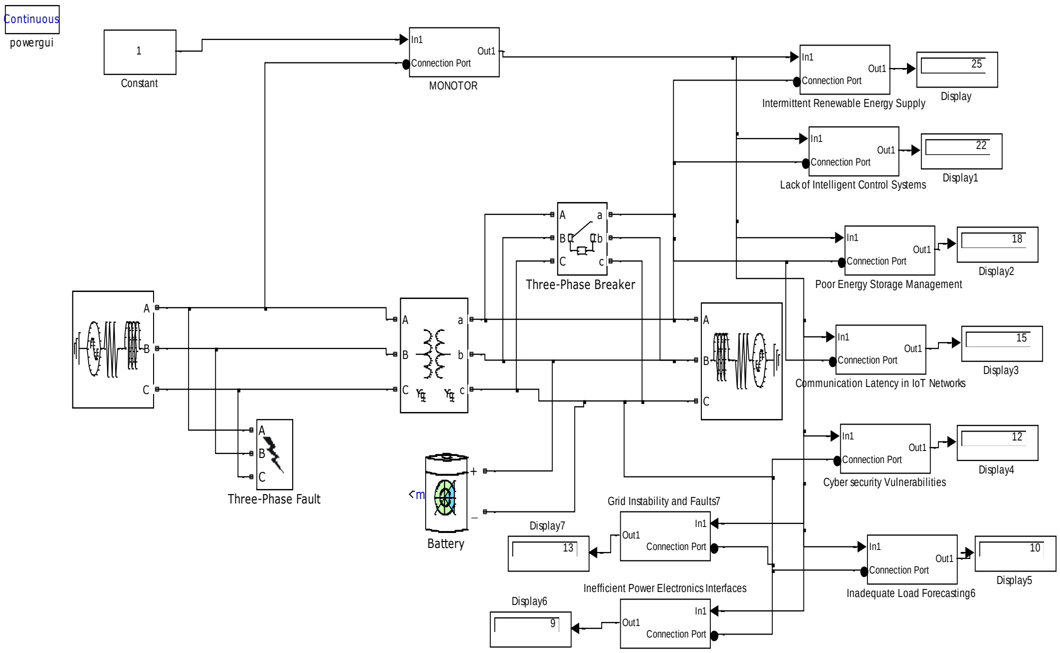

Fig 1.0 Conventional SIMULINK model for development of micro grid performance

3.1.2 Development of IoT Rule Base

To address the identified causes of poor performance, an IoT-based fuzzy inference system was developed. This system integrated two inputs: the causes of poor performance and the control system. The output represents the system's overall performance improvement. Figure 2 illustrates the IoT fuzzy inference system used to reduce the causes of poor performance. Figure 3 shows the IoT rule base developed to improve microgrid performance. The IoT rule base employed fuzzy logic to adaptively manage the control system's response to various performance issues. Some of the rules include:

Rule 1: If the causes of poor development performance are high and the control system is ineffective, the result is "unimproved developed microgrid performance."

Rule 2: If the causes are partially high and the control system is partially ineffective, the result remains "unimproved."

Rule 3: If the causes are low and the control system is effective, the result is "improved developed microgrid performance.

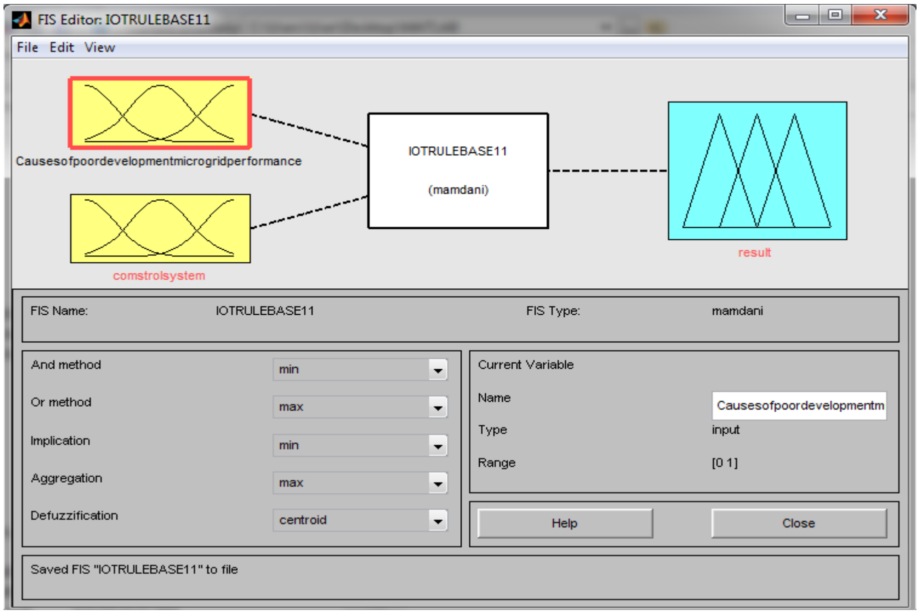

Fig 2.0: An IOT fuzzy inference system

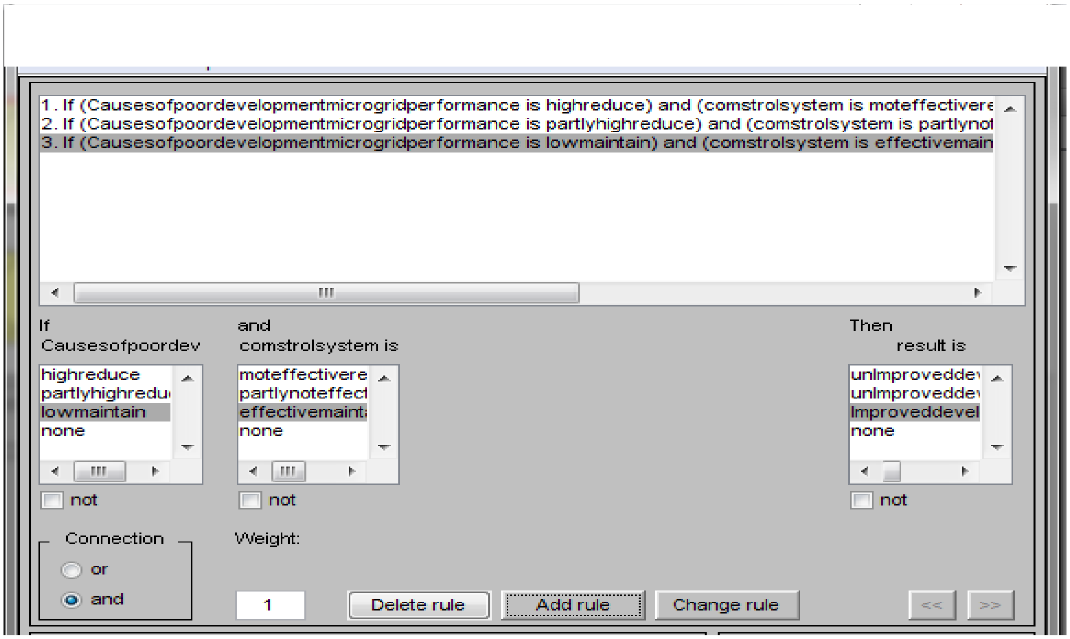

Figure 3.0: An IOT rule base performance

It reduce the causes of poor developed micro grid performance The comprehensive detailed IOT rule base to reduce the causes of poor development micro grid performance was in table 2.0

Table2.0: Comprehensive detailed IOT rule base to reduce the causes of poor development of micro grid performance

1	if causes of poor development micro grid performance is high reduce	and control system is not effective rectify	Then the result is un improved developed micro grid performance
2	if causes of poor development micro grid performance is partly high reduce	and control system is partly not effective rectify	Then the result is un improved developed micro grid performance
3	if causes of poor development micro grid performance is low reduce	and control system is effective maintain	Then the result is improved developed micro grid performance

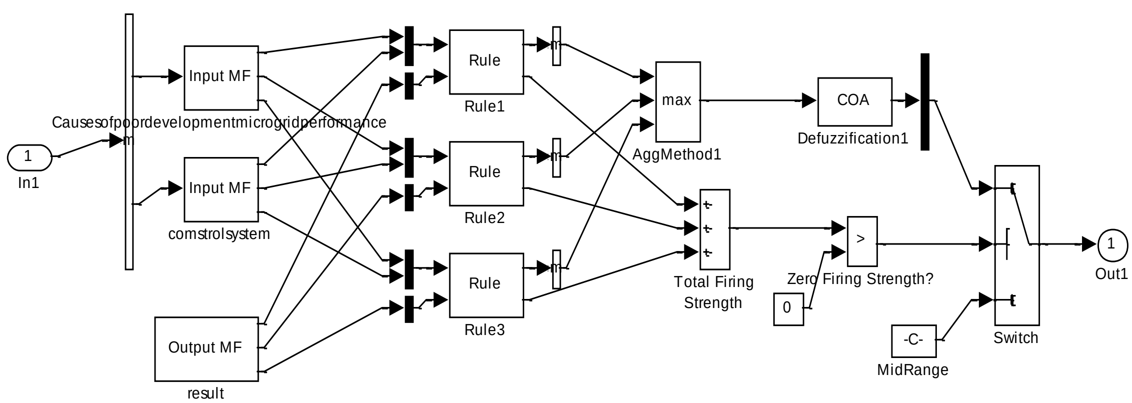

Fig 4.0: Operational mechanism of comprehensive detailed IOT rule base

Figure 4 demonstrates the operational mechanism of this rule base control System designs **that reduce the causes of poor** development micro grid performance. It also shows control system designed to enhance the efficacy of microgrid performance, incorporating the IoT-based rule and the conventional SIMULINK model.

3.1.3 Control System Design

A control system was designed to enhance the efficacy of microgrid performance, incorporating the IoT-based rule base and the conventional SIMULINK model. Figure 5 shows the control system architecture developed to optimize microgrid operations. Algorithm for System Integration was also developed.

The algorithm used for system integration followed these steps:

1. Characterize and establish causes of poor microgrid performance.
2. Design a conventional SIMULINK model for microgrid performance.
3. Develop an IoT rule base.
4. Design and integrate a control system based on the IoT rule base.
5. Evaluate the system's performance and validate improvements.

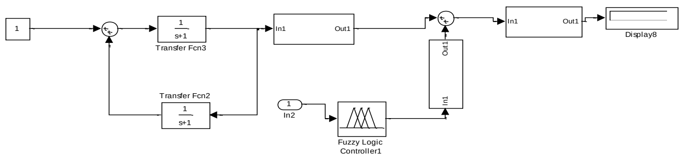

Figure 5.0: Control System for Micro Grid performance

The Algorithm can be specified further as shown below

1. characterize and established causes of poor development micro grid performance
2. Identify Intermittent Renewable Energy Supply
3. Identify Lack of Intelligent Control Systems
4. Identify Poor Energy Storage Management
5. Identify Communication Latency in IoT Networks
6. Identify Cyber security Vulnerabilities
7. Identify Inadequate Load Forecasting
8. Identify Grid Instability and Faults
9. Identify Inefficient Power Electronics Interfaces
10. Design a conventional SIMULINK model for development micro grid performance and integrate 2 through 10
11. Develop an IOT rule base to reduce the causes of poor development micro grid performance
12. Design a control system
13. Integrate 11 and 12
14. Integrate 13 into 10
15. Did the causes of poor development micro grid performance reduce when13 was integrated into 10 ?
16. IF NO go to 14.
17. IF yes go to 18
18. Improved developed micro grid performance
19. Stop
20. End

3.1.4: SIMULINK Model for IoT-Integrated System

The final step was to implement the IoT-integrated control system into the conventional SIMULINK model to observe improvements in microgrid performance. Figure 6 displays the SIMULINK model for the IoT-integrated control system. The design SIMULINK model for improving the development of an intelligent based internet of things (IOT) integrated control system for optimizing micro grid performance was also shown in figure 6

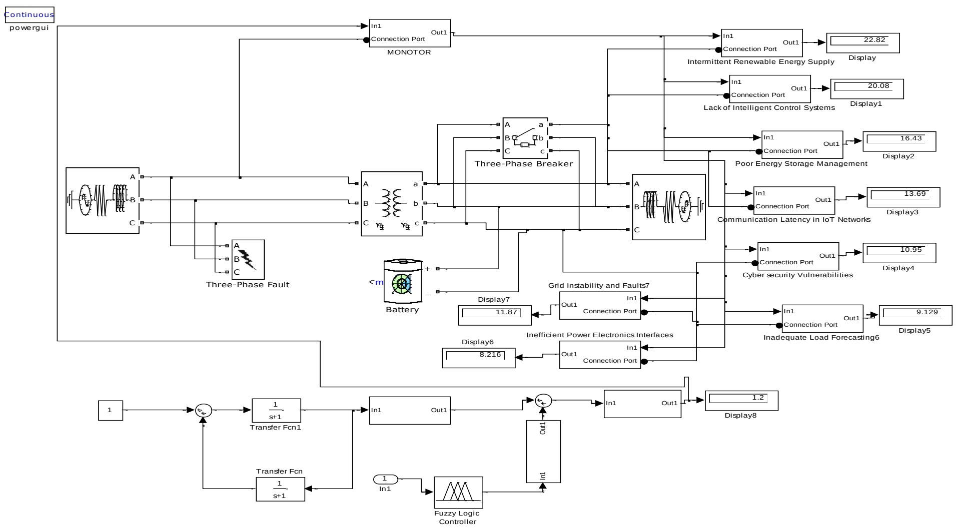

Figure 6.0: SIMULINK Model of intelligent based internet of things (IOT) integrated control system

1. Percentage Improvement in Reducing Intermittent Renewable Energy Supply Issues

The percentage improvement in the reduction of Intermittent Renewable Energy Supply as a cause of poor microgrid performance using an Intelligent (IoT)-based Integrated Control System was calculed, two data are requested which were:-

25% Conventional Intermittent Renewable Energy Supply and

22.8% IoT-based intermittent Renewable Energy Supply.

Then improvement = 25%−22.8% = 2.2%

Thereore % Improvement = 2.2\%

Result:

The implementation of an Intelligent (IoT)-based Integrated Control System results in a 2.2% improvement in reducing issues caused by intermittent renewable energy supply.

2. Percentage Improvement in Reducing Grid Instability and Faults

To calculate the percentage improvement in the reduction of Grid Instability and Faults as a cause of poor microgrid performance using an Intelligent (IoT)-based Integrated Control System. The data were :-

Conventional Grid Instability and Faults: 13%

IoT-based Grid Instability and Faults: 11.9%

Calculation:

Improvement=13%−11.9%=1.1%

% Improvement =1.1%

Result:

The implementation of an Intelligent (IoT)-based Integrated Control System results in a 1.1% improvement in reducing grid instability and faults.

The results obtained were as shown in figures 7 and 8. Validation, justification and percentage improvement in the reduction of **causes of poor** development micro grid performance with and without intelligent based (IOT) integrated control system, were also shown in table 3 and 4.

3.2 RESULTS

3.2.1 Improvement in Intermittent Renewable Energy Supply

The improvement in the reduction of the intermittent renewable energy supply issue was analyzed by comparing the conventional system to the IoT-integrated control system.

Table 3 comparison of conventional and Intelligent based (IOT) integrated control system for Intermittent Renewable Energy Supply

Time (s)	Conventional Performance (%)	IoT-Integrated Control System Performance (%)
1	25	22.8
2	25	22.8
3	25	22.8
4	25	22.8
10	25	22.8

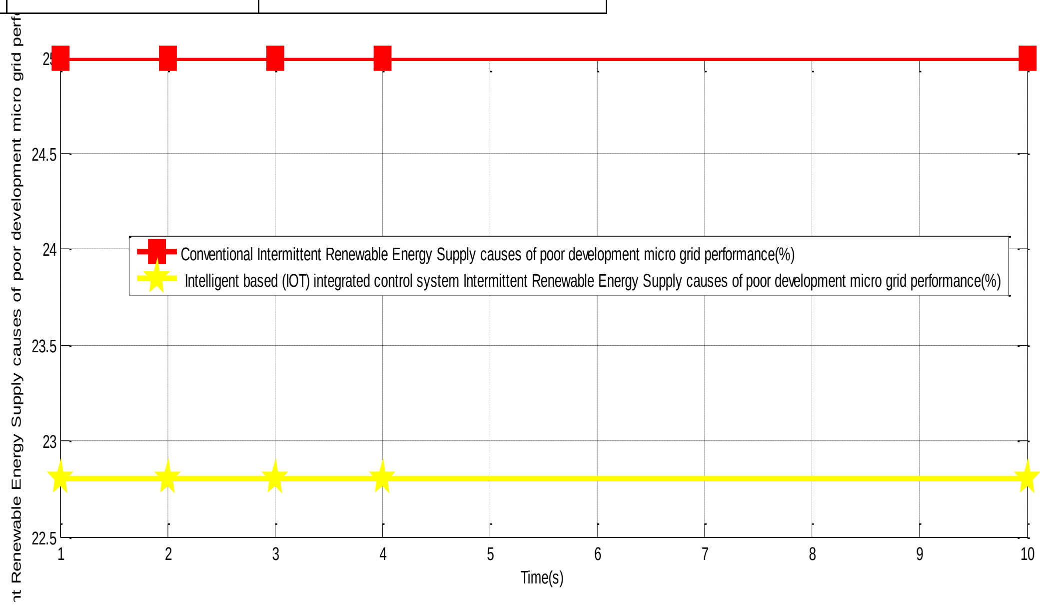

Figure 7: Comparison of conventional and Intelligent based (IOT) integrated control system

The Intermittent Renewable Energy Supply causes poor development micro grid performance. For conventional controller, the intermittent renewable energy supply caused by poor development of micro grid performance was

25%. On the other hand, when an intelligent based (IOT) integrated control system was input in the system, it automatically reduced to22.8%.

3.2.2 Improvement in Grid Instability and Faults

Similarly, the reduction in grid instability and faults was measured as shown in ftable 4.0

Table 4.0: Comparison of conventional and Intelligent based (IOT) integrated control system

Time (s)	Conventional Performance (%)	IoT-Integrated Control System Performance (%)
1	13	11.9
2	13	11.9
3	13	11.9
4	13	11.9
10	13	11.9

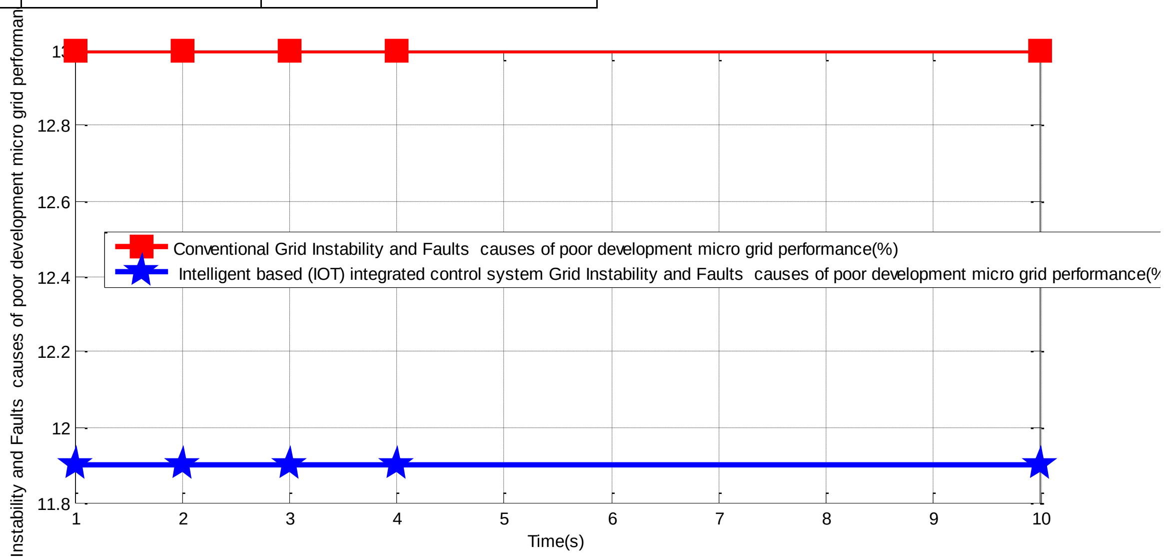

Figure 8.0: Comparison of conventional and Intelligent based (IOT) integrated control system

Grid instability and faults caused by poor development of micro grid performance were shown in graph of figure 8.0. The conventional grid instability and faults caused by poor developed micro grid performance were 13%. Meanwhile, when an intelligent based (IOT) integrated control system was incorporated into the system, it drastically reduced to11.9%. Finally, with these results obtained, the percentage improvement in developed micro grid performance when an Intelligent based (IOT) integrated control system was inserted in the system was 1.1%.

In summary, an intelligent IoT-integrated control system demonstrates significant potential for improving microgrid performance. By enabling real-time monitoring, decision-making algorithms, and seamless communication between distributed energy resources, the system enhances microgrid resilience, reduces energy losses, and improves operational efficiency. The application of AI and machine learning techniques in the control system further contributes to optimizing power distribution and balancing, making it more adaptable to fluctuating load and renewable energy supply. Through the integration of IoT and intelligent control, the causes of poor development in microgrid systems—such as intermittent renewable energy supply and grid instability—were reduced by 2.2% and 1.1%, respectively. This study highlights the importance of developing intelligent, autonomous systems to address the challenges faced by microgrids and further underscores the potential for scalable, sustainable energy solutions.

4.0 CONCLUSION

The development of an intelligent-based Internet of Things (IoT) integrated control system presents a transformative solution for optimizing microgrid performance. By leveraging real-time data acquisition, intelligent decision-making algorithms, and advanced communication technologies, the proposed system enhances the operational efficiency, reliability, and sustainability of microgrids. The integration of IoT enables seamless monitoring and control of distributed energy resources, load demand, and storage systems, while intelligent control strategies—such as machine learning and fuzzy logic—facilitate adaptive responses to dynamic grid conditions. This approach not only minimizes energy losses and improves power quality but also ensures effective load balancing and renewable energy integration. Ultimately, the intelligent IoT-based control framework offers a scalable and robust platform for future smart grid applications, paving the way for more resilient, autonomous, and environmentally friendly energy systems. Further research and development in this field will continue to advance the potential of micro grids as key components of modern energy infrastructure. The conventional Intermittent Renewable Energy Supply causes of poor development micro grid performance was 25%. On the other hand, when an Intelligent based (IOT) integrated control system was input in the system, it automatically reduced to22.8% and the conventional Grid Instability and Faults causes of poor development micro grid performance were 13%. Meanwhile, when an Intelligent based (IOT) integrated control system was incorporated into the system, it drastically reduced to11.9%. Finally, with these results obtained, the percentage improvement in developed micro grid performance when an Intelligent based (IOT) integrated control system was inserted in the system was 1.1%.

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