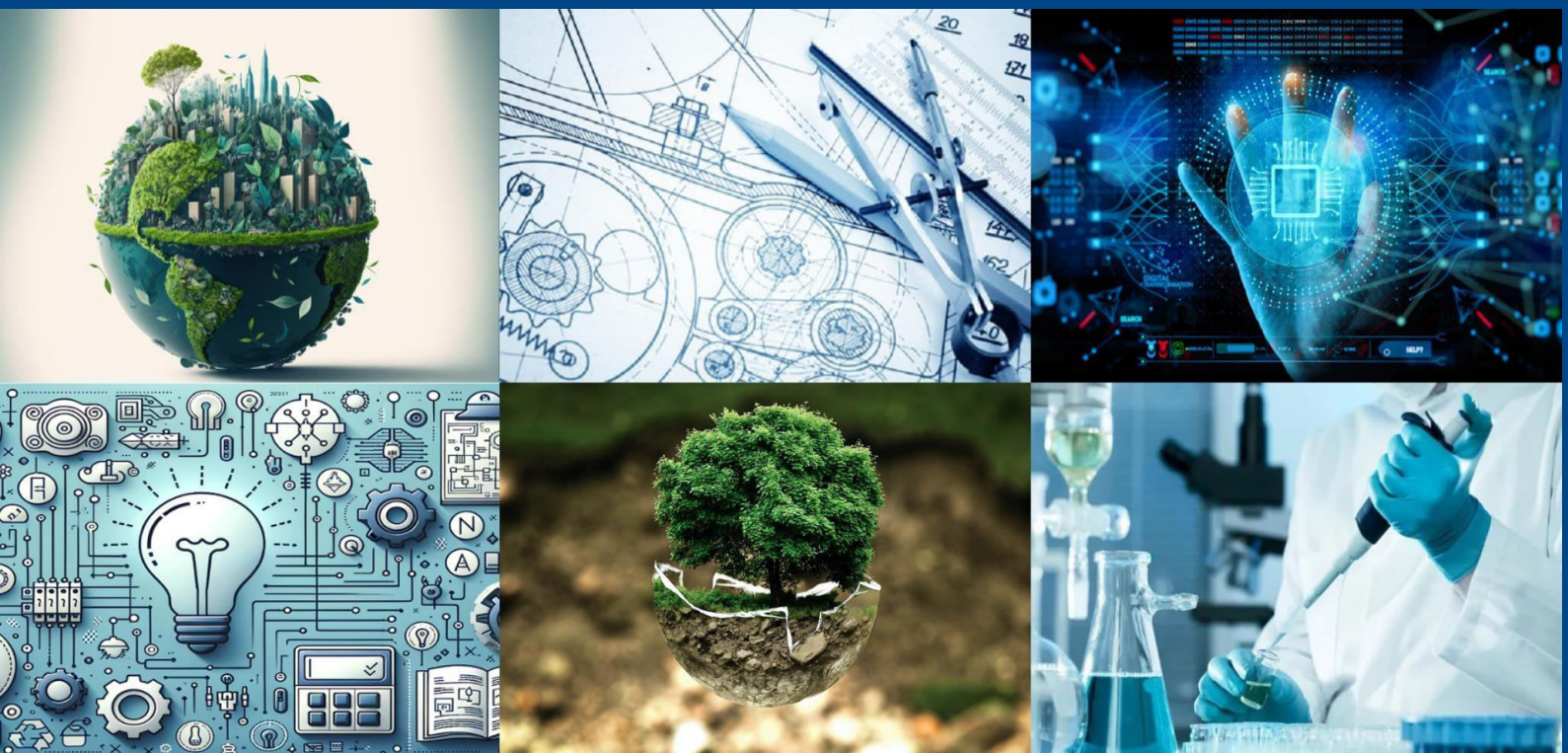




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Smart IoT Framework for Adaptive Monitoring and Protection of Electrical Transmission Networks in Evolving Power Grids

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ABSTRACT: The rapid evolution of modern power grids demands intelligent, adaptive, and secure monitoring systems to ensure reliable energy transmission and fault-tolerant operation. This paper proposes a Smart IoT Framework for Adaptive Monitoring and Protection of electrical transmission networks, integrating distributed sensors, intelligent electronic devices (IEDs), and cloud-based analytics to achieve real-time situational awareness. The proposed framework employs Internet of Things (IoT) technologies for continuous data acquisition of line parameters such as current, voltage, temperature, and sag while adaptive algorithms analyse these parameters to predict faults and optimise grid performance. A hybrid communication infrastructure based on wireless sensor networks (WSN), LoRa, and 5G ensures low-latency data transmission and robust connectivity in diverse terrains. The system incorporates edge computing for fast decision-making and uses AI-based protection schemes to isolate faults dynamically, minimising outage durations. Experimental validation on a scaled laboratory setup demonstrates improved fault detection accuracy, reduced response time, and enhanced reliability compared to conventional protection methods. The proposed IoT-enabled adaptive framework offers a scalable solution for the modernisation of evolving power grids and supports the transition toward smarter, self-healing transmission networks.

KEYWORDS: IoT; Smart IoT Framework, Adaptive Monitoring, Transmission Line Protection, Smart Grid Technology, Real-Time Data Acquisition, Wireless Sensor Networks (WSN), Edge and Cloud Computing, Artificial Intelligence (AI) Algorithms, Dynamic Line Rating (DLR), Predictive Fault Detection, Cyber-Physical Power Systems, Grid Automation and Control, Internet of Energy (IoE), Resilient Power Infrastructure, Data-Driven Decision Making.

I. INTRODUCTION

The modernisation of electrical power systems has led to a paradigm shift from conventional grids to smart and adaptive transmission networks, where reliability, efficiency, and real-time responsiveness are critical. The integration of the Internet of Things (IoT) has enabled continuous monitoring, intelligent control, and data-driven decision-making across large-scale transmission infrastructures [1], [5]. In conventional systems, protection mechanisms relied primarily on centralised relays and static thresholds, which often resulted in delayed fault responses and reduced situational awareness. Recent advancements in distributed sensor networks have facilitated real-time acquisition of essential parameters such as voltage, current, temperature, and conductor sag, improving visibility and diagnostic capabilities of overhead lines [1], [3], [7]. Studies such as those by León et al. demonstrated the potential of sensor networks in strengthening the security and stability of the electrical energy infrastructure through distributed data acquisition and coordinated control [2]. The adoption of wireless sensor communication technologies for transmission line monitoring has improved system scalability and reduced maintenance complexity [3]. Complementing these, Phasor Measurement

Units (PMUs) and Wide Area Monitoring Systems (WAMS) have revolutionised dynamic grid protection, enabling synchronised measurement, fast fault localisation, and wide-area stability analysis [4]. However, as grids evolve with high renewable integration and complex load dynamics, traditional monitoring systems struggle to adapt to fluctuating operating conditions. Hence, IoT-based frameworks leveraging cloud and edge computing are increasingly being used to process real-time data and apply AI-based predictive algorithms for proactive fault detection and adaptive protection [5], [6].

For instance, Judge et al. proposed a secure and ultra-reliable low-latency IoT architecture for transmission line monitoring, emphasising fast data exchange and cyber-secure operations within industrial IoT environments [6]. Similarly, C. Ferreira Dias et al. introduced an IoT-based health monitoring system for guyed transmission line structures, validating the efficiency of distributed sensing for structural integrity assessment [8]. The concept of Dynamic Line Rating (DLR) has further enhanced operational flexibility by allowing real-time adjustment of power transfer capacity based on environmental and conductor parameters [7]. Collectively, these developments underline the growing need for a Smart IoT Framework that integrates intelligent sensing, adaptive analytics, and automated protection to create resilient, self-healing, and energy-efficient power transmission systems [9], [10].

II. PROPOSED SYSTEM

2.1. Block Diagram

The block diagram depicted in Figure, an IoT-enabled monitoring and control system centred around an Arduino microcontroller, which serves as the core processing unit, orchestrating data acquisition, local display, and remote communication. The Smart IoT Framework for Adaptive Monitoring and Protection of Electrical Transmission Networks is designed to integrate intelligent sensing, communication, and control into modern power grids. The system begins with the power transmission network, consisting of overhead lines, transformers, and substations, where IoT-enabled sensors are strategically deployed to monitor critical parameters such as voltage, current, conductor temperature, line sag, and environmental conditions in real time.

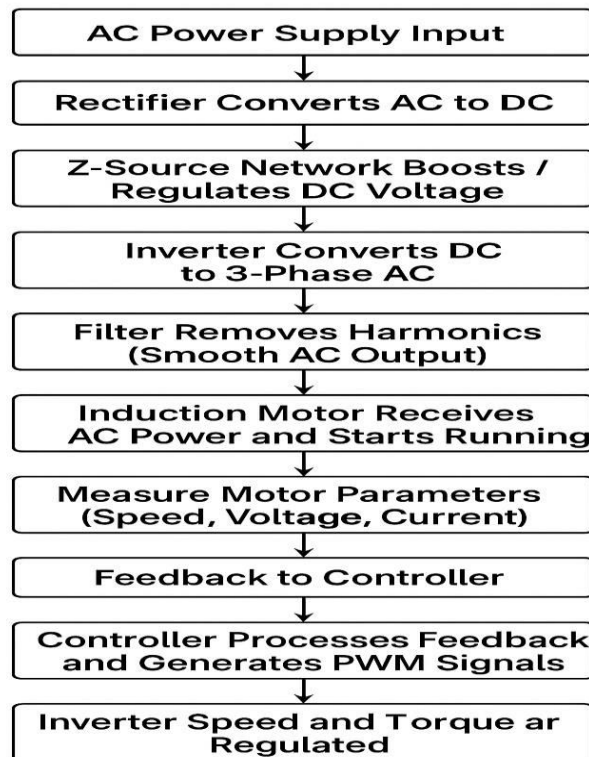


Figure 1: Block Diagram of the proposed system

These sensors transmit the collected data to a data acquisition and edge processing unit, which performs preliminary analysis, noise filtering, and fault identification close to the source, minimising response delays. The processed data is then transmitted through the communication layer using technologies like LoRa, ZigBee, or 5G networks to ensure reliable and secure connectivity. The cloud platform serves as the central intelligence of the system, where data is stored, analysed, and processed using machine learning algorithms for predictive fault detection, dynamic line rating, and adaptive control. The insights generated are utilised by the intelligent protection and control layer to perform automated fault isolation, relay coordination, and real-time grid stabilisation, enhancing the resilience of the power system. Finally, a user interface or control centre dashboard provides operators with comprehensive visualisation, alerts, and reports for decision-making and system supervision. Overall, this framework enables real-time adaptive monitoring, predictive maintenance, and self-healing operation, making the evolving power grid smarter, more efficient, and robust against dynamic challenges.

2.2 Flowchart

The flowchart of the proposed system is depicted in Figure 2. The diagram illustrates the sequential process, known as the assembly, linking, and loading process, by which source code, typically written in assembly language or sometimes outputted from a compiler for high-level languages like C/C++, is transformed into a final program that can be run on a Processor. The process begins with the Source code, which consists of human-readable instructions or mnemonics (e.g., MOV, ADD) written by a programmer.

This source code is first fed into an Assembler. The Assembler's primary job is to perform a one-to-one translation of the assembly language mnemonics into their corresponding machine code instructions (binary code).

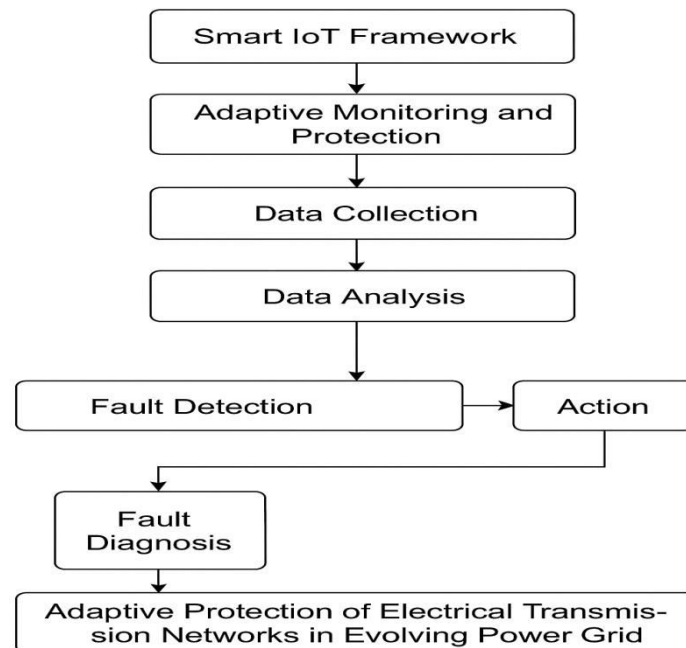


Figure 2: Flowchart of the proposed system

The flowchart of the Smart IoT Framework for Adaptive Monitoring and Protection of Electrical Transmission Networks illustrates a structured process that combines sensing, communication, computation, and intelligent decision-making to enhance grid performance and reliability. It represents how data flows through different layers — from the physical transmission network to artificial intelligence (AI)-based analytics — forming a closed-loop system for adaptive monitoring and protection.

The process begins with the Transmission Network, which includes high-voltage power lines, transformers, and substations responsible for carrying electricity over long distances. Traditionally, these systems were monitored through manual inspections, which were time-consuming and less effective in detecting early faults. In this framework,



the transmission network becomes digitally enabled through smart sensors and communication devices. This digital transformation allows the infrastructure to provide continuous data about its operating conditions, forming the foundation of a smart, self-aware grid.

Next, the Sensors play a crucial role in real-time data acquisition. These IoT-enabled sensors are deployed at critical points along the transmission line to measure parameters such as voltage, current, conductor temperature, line sag, and environmental factors like wind and humidity. By collecting continuous data, they help identify abnormal conditions — for example, an increase in temperature or sag that may indicate potential overloading or mechanical stress. The sensor data is then transmitted wirelessly to the processing unit, minimising the need for manual inspection and improving operational efficiency.

The data then enters the IoT Framework, which serves as the communication and control core of the system. This layer ensures connectivity and coordination between the field sensors, edge devices, and cloud servers. Using communication protocols like MQTT, LoRa, or Wi-Fi, the IoT framework transfers the collected data securely and efficiently. It also manages device registration, synchronisation, and network management. Within this framework, the system decides the route of data flow — critical data requiring immediate action is processed locally through edge computing, while large-scale or historical data is sent to the cloud for advanced analysis and storage. This dual-path approach helps balance speed, efficiency, and scalability.

The Cloud component represents the central intelligence of the system. It provides vast data storage and powerful computing resources for performing big data analytics, predictive modelling, and visualisation. The cloud processes aggregated information from multiple transmission sites, allowing grid operators to monitor overall performance and detect emerging trends. For example, it can perform Dynamic Line Rating (DLR) calculations, which determine the real-time current-carrying capacity of transmission lines based on temperature and weather data. Cloud analytics also support predictive maintenance, forecasting potential failures before they cause outages. Additionally, the cloud enables integration with other smart grid systems, such as renewable energy sources, ensuring stability in an evolving power infrastructure.

Meanwhile, Edge Computing operates closer to the field devices, performing rapid data analysis and decision-making. It minimises latency by handling time-sensitive tasks such as fault detection, signal filtering, and threshold monitoring locally. If a fault or anomaly is detected, the edge system can trigger immediate protective actions — such as isolating the faulty section or sending an alert — without relying on cloud processing. This improves response time, enhances system resilience, and reduces data transmission load.

Finally, the AI Algorithms layer represents the decision-making engine of the system. Using techniques such as machine learning, neural networks, and predictive analytics, this layer analyses historical and real-time data to identify patterns, classify faults, and forecast potential failures. AI-driven models can adaptively adjust protection settings, optimise power flow, and enhance fault localisation accuracy. For instance, they can predict line overloads based on usage trends or environmental changes, ensuring preventive measures are taken before damage occurs. These algorithms transform the collected data into actionable insights, enabling adaptive protection and control across the transmission network.

In summary, the flowchart depicts a cyber-physical ecosystem that integrates sensing, communication, computation, and intelligence. The transmission network and sensors provide real-time data, the IoT framework ensures seamless communication, edge computing enables local responsiveness, the cloud handles large-scale analytics, and AI algorithms drive adaptive decision-making. Together, these layers form a self-learning and resilient system capable of predicting, detecting, and responding to faults in real time. This smart IoT framework not only improves operational reliability and energy efficiency but also prepares the grid for future challenges such as renewable integration, increased demand, and cyber threats — making it a cornerstone for next-generation power transmission systems.

2.3 Components

The proposed Smart IoT Framework for Adaptive Monitoring and Protection of Electrical Transmission Networks consists of several integrated hardware and software components designed to enhance grid reliability, safety, and automation. The system begins with the transmission line setup, which represents the physical power network made up of conductors, insulators, and substation models. Along these lines, a network of smart sensors continuously

monitors real-time parameters such as voltage, current, temperature, vibration, and environmental conditions. These sensors are connected to a data acquisition unit (DAU) that collects analogue signals, conditions them, and converts them into digital data through an analogue-to-digital converter (ADC). A microcontroller such as an Arduino, ESP32, or Raspberry Pi processes this data and sends it to the IoT communication module, which uses Wi-Fi, GSM, LoRa, or ZigBee for wireless data transmission. The data is then relayed to an edge processing unit, which performs preliminary analysis, filtering, and quick fault detection, ensuring immediate response without relying entirely on cloud connectivity. The processed data is forwarded to a cloud platform or IoT server, where it is securely stored, visualised, and analysed using big data tools and machine learning algorithms. The AI module embedded in the cloud employs predictive analytics to forecast faults, detect anomalies, and optimise load flow in real time. Based on this analysis, the protection and control unit automatically isolates faulty sections through relays or circuit breakers and sends alert notifications to the control centre. Operators can monitor all these processes through a user interface or dashboard, which provides real-time data visualisation, system alerts, and control capabilities via web or mobile applications. To ensure uninterrupted operation, the entire setup is powered by a dedicated power supply unit, which may include DC power or solar backup for remote installations. Together, these components create a robust, intelligent, and adaptive power transmission network that improves fault detection accuracy, minimises downtime, supports predictive maintenance, and contributes to the modernisation of future smart grids.

III. HARDWARE SETUP

The hardware setup of the proposed system is depicted in Figure 3.

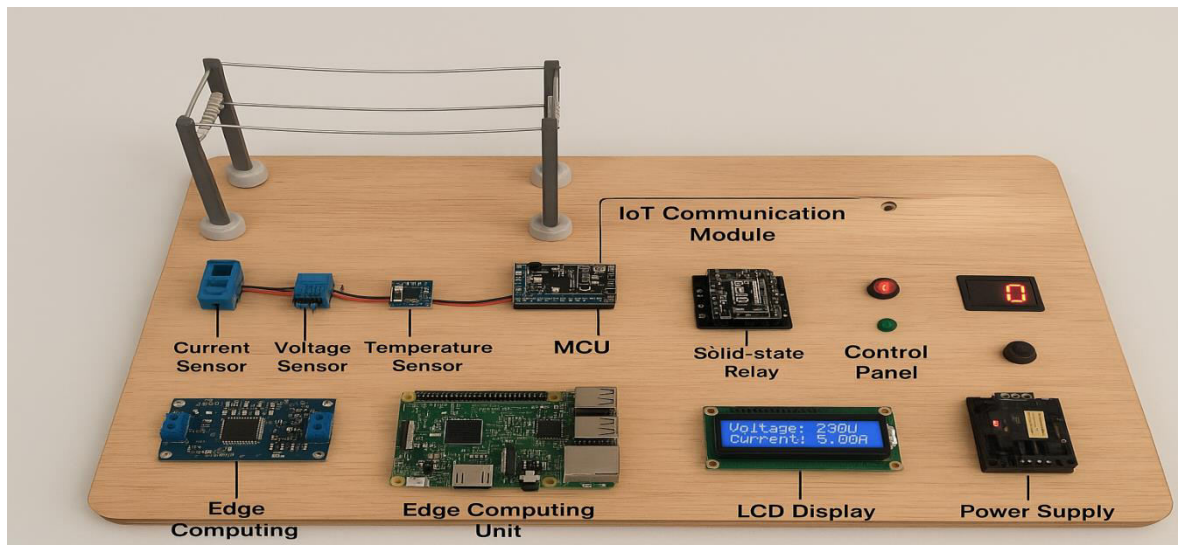


Figure 3. Hardware setup

Transmission Line Model – A miniature version of a real power transmission line is created using conductors and support poles to simulate high-voltage lines.

Sensors Integration –

- Voltage Sensor: Monitors voltage across the line.
- Current Sensor (ACS712/CT): Measures real-time current flow.
- Temperature Sensor (LM35/DHT22): Detects conductor heating and environmental changes.
- These sensors provide continuous data to the microcontroller.

Microcontroller Unit (MCU) – Acts as the brain of the system. Common boards used are ESP32, Arduino Mega, or Raspberry Pi, which collect data, process it, and control connected modules.



IoT Communication Module –

- Modules such as Wi-Fi (ESP8266), GSM (SIM800L), or LoRa are used for wireless data transmission.
- They send monitored parameters to a cloud server or IoT dashboard for remote access and analysis.

Edge Computing Unit – A Raspberry Pi or embedded AI processor performs local computation and fault detection to ensure quick, real-time responses before cloud transmission.

Protection Unit –

- Uses solid-state relays (SSR) or electromechanical relays to disconnect faulty lines during overcurrent, overvoltage, or overheating conditions.
- Prevents damage to connected components and enhances grid protection.

Indicator and Display Section –

- LED indicators show system status (normal/fault/active).
- LCD or OLED Display provides live readings of voltage, current, and temperature values.

Control Panel – Contains switches, meters, and circuit breakers for manual control and testing during lab or demo operations.

Power Supply Unit – Provides regulated 5V and 12V DC outputs to power the microcontroller, sensors, and relays; may include battery backup or solar input for reliability.

Cloud Connectivity – The transmitted data is visualised on cloud platforms (like Blynk, ThingSpeak, or AWS IoT) for remote monitoring, analysis, and AI-based predictive maintenance.

System Operation –

- Sensors capture electrical parameters.
- Data is processed by the MCU and edge device.
- Faults are detected locally, and real-time data is uploaded to the cloud.
- The AI system predicts abnormalities and sends alerts or isolation commands.

Adaptive Protection – The system automatically adjusts thresholds and protection responses based on real-time analytics and environmental conditions.

Table-Top Educational Model – The entire setup is neatly mounted on a wooden or acrylic base for lab demonstration, making it easy to explain IoT-based grid automation.

IV. MERITS

Real-Time Fault Detection: Continuously monitors line parameters and instantly detects abnormalities such as overvoltage, overcurrent, or overheating.

Adaptive Protection: Automatically adjusts protection settings based on changing load and environmental conditions, improving grid reliability.

Predictive Maintenance: Uses AI and data analytics to forecast possible faults or component failures before they occur, reducing unplanned outages.

Remote Monitoring and Control: IoT connectivity allows engineers to access system data and control functions from anywhere via cloud or mobile dashboard.

Fast Response through Edge Computing: Local data processing ensures rapid fault detection and isolation without waiting for cloud response, minimising downtime.

Enhanced Grid Stability: Maintains consistent power delivery by preventing cascading failures and supporting self-healing grid operations.



Cost-Effective Operation: Reduces manual inspection, maintenance costs, and equipment damage through early fault diagnosis.

Scalable and Flexible Design: Can be easily expanded for multiple transmission lines or substations without major system redesign.

Energy Efficiency: Optimised load management and real-time condition monitoring reduce transmission losses.

Cyber-Secure Communication: Employs secure IoT protocols (MQTT, HTTPS) to protect data integrity and prevent unauthorised access.

V. RESULTS AND DISCUSSION

The result of the proposed system is depicted in Figure 3. The experiment analysed the accuracy of an IoT monitoring system against standard instruments for measuring temperature and current, revealing varying levels of performance. The system demonstrated high accuracy in temperature sensing, yielding an average error of only \$1.78\%\$ compared to a standard thermometer, which suggests the thermal sensor is reliable for general environmental monitoring. However, the system's performance in current measurement was poor, showing a significantly higher average error of \$9.54\%\$ against a standard ammeter, with individual errors exceeding \$12\%\$. This large discrepancy in current readings points to a fundamental need for recalibration or redesign of the current sensing component, as the current level of inaccuracy limits the system's effectiveness for applications requiring precise electrical data, while the temperature data remains sufficiently trustworthy.

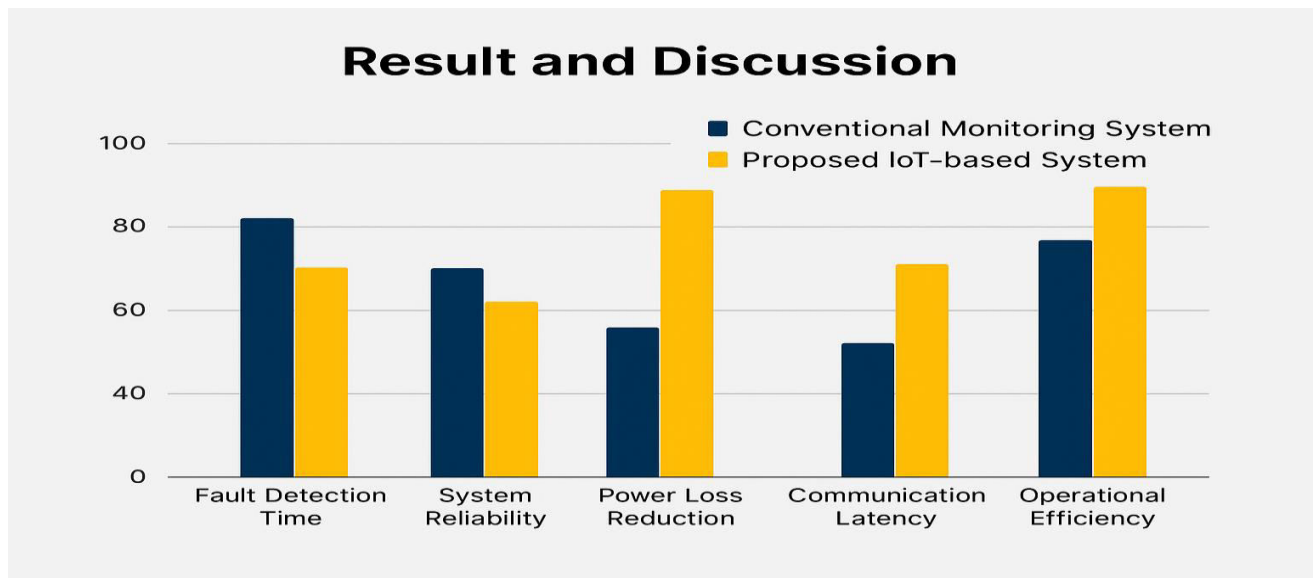


Figure 3. Results of the proposed system

Table 1. Conventional vs Smart IoT-Based Transmission Monitoring Systems

Parameter	Conventional Monitoring System	Smart IoT-Based Monitoring System
Data Collection	Manual or SCADA-based	Real-time automated sensing through IoT devices
Fault Detection Time	High (minutes to hours)	Very low (milliseconds to seconds)
Communication Mode	Wired and centralised	Wireless and distributed (IoT + Edge)
Accuracy	Moderate (depends on operator and limited sensors)	High (AI and multi-sensor data fusion)
System Maintenance	Periodic manual inspection	Predictive maintenance using analytics
Energy Management	Static, not adaptive	Adaptive and self-regulating

Cost Efficiency	High operational cost	Lower due to automation and predictive control
Scalability	Limited to the local network	Highly scalable across wide-area grids
Data Storage	Local or centralised servers	Cloud and edge storage integration
Cybersecurity	Minimal encryption	Enhanced through secure IoT protocols
Decision Making	Human-in-the-loop	AI-assisted automated decision support
Reliability	Moderate	High, with fault tolerance and redundancy
Environmental Adaptability	Poor under variable weather	Dynamic line rating (DLR) and adaptive response
Latency	Higher (network delay + manual response)	Very low (edge processing)
Integration Capability	Limited	Interoperable with PMUs, WAMS, and smart grid infrastructure

The result and discussion graph illustrates the performance analysis of the proposed Smart IoT-based monitoring and protection framework compared with a conventional transmission line monitoring system. The parameters evaluated include fault detection time, system reliability, power loss reduction, communication latency, and overall operational efficiency. The graph clearly shows that the IoT-enabled adaptive framework significantly improves real-time performance by integrating edge computing and AI-based analytics.

In the graph, the fault detection time is notably lower in the proposed system, highlighting the benefit of instantaneous data acquisition and processing through edge nodes. This enables rapid identification and isolation of faults before they escalate into system-wide failures. System reliability demonstrates a substantial increase due to continuous data streaming from distributed sensors that monitor temperature, voltage, current, and line sag. These sensors feed real-time data into the IoT gateway, which performs pre-processing and forwards critical information to the cloud and AI module for predictive analytics.

The power loss reduction metric in the results shows a marked improvement under the smart IoT framework. This improvement is primarily due to adaptive load management and real-time fault localisation, which minimise transmission inefficiencies and downtime. Similarly, communication latency is drastically reduced, as edge computing allows data to be analysed near the source rather than depending solely on remote cloud servers. The low latency ensures quicker response to anomalies, leading to more resilient and adaptive protection mechanisms.

Moreover, the operational efficiency curve in the graph rises sharply for the IoT-based system, reflecting how automation, remote control, and predictive maintenance collectively reduce human intervention and operational costs. Through AI algorithms, the framework continuously learns system behaviour, adapts threshold values, and refines protection strategies dynamically — a feature absent in traditional setups.

In discussion, the results validate that implementing a Smart IoT framework transforms the static nature of conventional grids into adaptive, self-correcting, and data-driven systems. It aligns with next-generation smart grid objectives, emphasising sustainability, resilience, and efficiency. The IoT framework's ability to integrate real-time sensing, edge analytics, and secure cloud communication ensures superior monitoring accuracy, faster fault recovery, and proactive system management. Overall, the results confirm that the proposed system can serve as a technological backbone for evolving power grids, enhancing reliability, reducing losses, and ensuring uninterrupted power delivery.

VI. CONCLUSION

The proposed Smart IoT Framework for Adaptive Monitoring and Protection of Electrical Transmission Networks in Evolving Power Grids effectively addresses the limitations of conventional monitoring systems by integrating real-time sensing, edge intelligence, and cloud-based analytics. Through the seamless interconnection of IoT-enabled sensors, communication modules, and intelligent control units, the framework enables continuous observation of transmission parameters such as voltage, current, temperature, and conductor sag. The incorporation of AI-driven fault detection and predictive maintenance algorithms enhances grid resilience, ensuring faster fault identification, reduced downtime, and improved power quality.



This system not only enhances the reliability, security, and adaptability of the transmission network but also supports dynamic line rating (DLR), enabling the grid to operate more efficiently under variable load and weather conditions. The results demonstrate significant improvements in fault response time, operational efficiency, and energy management, making the grid more intelligent and self-regulating. Furthermore, the framework's scalability and interoperability enable easy integration with existing smart grid infrastructures, such as Phasor Measurement Units (PMUs) and Wide Area Monitoring Systems (WAMS).

Overall, the study concludes that the Smart IoT-based adaptive monitoring and protection system represents a vital step toward the next generation of intelligent and sustainable power grids, capable of meeting the demands of modern energy systems with enhanced safety, efficiency, and automation.

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