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International Journal of Advanced Electrical and Electronics Engineering

ISSN: 2278-8948

Volume 14 Issue 02, 2025

Review on Smart Grid Energy Distribution and Power System Management Using IoT Technology

[1]Ms. Aparna A. Gudhekar, [2]Prof. Suraj Mahajan, [3]Prof. Rohini Pochhi
[1]PG Scholar , Department of Electronics (Communication) Engineering
Tulsiramji Gaikwad-Patil College of Engineering & Technology, Nagpur, India
[2]Project Guide, Department of Electronics (Communication) Engineering
Tulsiramji Gaikwad-Patil College of Engineering & Technology, Nagpur, India
[3]Project Co-Guide, Department of Electronics (Communication) Engineering
Tulsiramji Gaikwad-Patil College of Engineering & Technology, Nagpur, India
Email: [1]aparnagudhekar@gmail.com, [2]suraj.ece@tgpcet.com

Peer Review Information

Submission: 05 Nov 2025

Revision: 25 Nov 2025

Acceptance: 17 Dec 2025

Keywords

Internet of Things (IoT), Smart Grid, Real-time Monitoring, Renewable Energy Integration, Fault Detection, Energy Efficiency.

Abstract

The rapid advancement of the Internet of Things (IoT) has revolutionized the operation and management of modern smart grids by enabling real-time monitoring, efficient energy utilization, and improved fault detection. This paper presents a comprehensive review of IoT-enabled smart grid systems, focusing on communication infrastructures, architectures, enabling technologies, and applications. The integration of IoT with smart grids enhances bidirectional communication, demand-side management, and renewable energy integration, while supporting automation and intelligent decision-making. The review also highlights major challenges such as scalability, interoperability, latency, cybersecurity, and data privacy, which must be addressed to ensure reliable deployment. Various studies and recent technological innovations are discussed to examine how IoT contributes to the resilience, sustainability, and efficiency of power systems. Furthermore, potential solutions and future research directions are explored, including cloud computing, edge intelligence, and advanced communication protocols. This review provides insights into the current state of IoT-based smart grids and their role in building sustainable energy infrastructures.

Introduction

The rapid pace of global digitalization has placed unprecedented emphasis on ensuring worldwide cybersecurity. Advances in online communication and greater transparency, especially in modern Western societies, have made scientific knowledge and technological breakthroughs more accessible through frequent publication in scientific journals [1–3]. Unfortunately, this openness means that cybercriminals and malicious state actors now have the same access to cutting-edge research as legitimate government scientists and researchers.

Machine learning research has led to the development of advanced algorithms and applications that help detect potential threats and respond to them effectively [4]. The term “internet barriers” refers to technical practices, protocols, and procedures designed to prevent threats and unauthorized access to online services, computers, and sensitive data [4].

Notably, the field of artificial intelligence saw significant progress in 2016, influencing areas like healthcare, voice-based assistance, and workforce automation. AI technologies have been leveraged to extract crucial information from extensive audit logs that help identify malicious intrusions [3].

Cyberattacks often succeed despite multiple failed attempts, giving attackers an advantage in the digital battlefield. In contrast, defenders must maintain near-perfect security to remain protected. Studies show that in 2017 alone, countless businesses, organizations, individuals, and applications suffered breaches, exposing private records, financial data, and confidential information [5]. When such data is leaked to the public or sold illegally, the consequences can be devastating. Numerous statistics highlight the profound impact of cyber threats on individuals, corporations, and institutions worldwide:

• Over $3.9 billion in stolen items as well as theft mitigation expenses were incurred in previous eras.

• There is likely to be a significant demand through 2022 for more than 20 million information technology positions.

• Institutions all across the world are expected to spend no less than $20 million annually on protecting their data protection.

• According to research, thieves earn more than $1 trillion a year for ransom.

Problem Identification

- Traditional grid limitations: Conventional power grids lack real-time monitoring and control, making them inefficient in detecting faults and preventing power outages.
- Increasing demand: Rising electricity consumption places stress on existing grid infrastructure, leading to frequent instability and failures.
- Renewable integration issues: Variable output from renewable sources such as solar and wind makes balancing supply and demand a major challenge.
- Fault detection delays: Manual inspection methods are time-consuming, often leading to delayed identification and rectification of grid faults.
- Energy losses: Transmission and distribution losses remain high due to poor monitoring of line conditions and equipment health.
- Lack of consumer engagement: Consumers have limited access to real-time energy usage data, reducing energy efficiency at the user end.
- Cybersecurity concerns: Growing connectivity through IoT introduces vulnerabilities in data privacy and grid protection.

Literature survey

A) Literature Review

Sharma R. et. al. 2022, This study investigates the application of IoT devices for real-time monitoring of power grids to enhance stability and reduce outages. Sensors were deployed on transformers and distribution lines to continuously measure voltage, current, and temperature. Data collected via IoT modules were analyzed using cloud-based platforms to predict faults and optimize load distribution. The system demonstrated a 15% reduction in energy losses and a 20% improvement in fault detection response time compared to conventional grids. The research highlights the importance of automated alerts, predictive maintenance, and two-way communication between control centers and field devices, showing that IoT integration enhances grid reliability and energy efficiency in urban and industrial environments.

Li X. et. al. 2022, The paper explores how IoT technology can support the integration of variable renewable energy sources like solar and wind into smart grids. A system of IoT sensors was designed to monitor real-time generation from distributed sources and coordinate power flow with storage systems. Using predictive analytics, the model balanced load demand and generation variability, improving grid stability. Experimental results showed a 12% increase in renewable energy utilization and reduced dependency on fossil-fuel-based backup generation. The study emphasizes the role of IoT in enabling dynamic load management, real-time energy balancing, and predictive control, ensuring a sustainable and efficient smart grid capable of handling renewable fluctuations without compromising reliability.

Patel K. et. al. 2023, This research presents a fault detection and automated response framework for IoT-enabled smart grids. The system utilizes a network of sensors to monitor voltage, current, and temperature at critical grid points. Data is transmitted to a central control unit for real-time processing, triggering automated actions such as load shedding or activation of cooling mechanisms. Field tests demonstrated a 25% reduction in downtime caused by transformer overheating and voltage fluctuations. The study underlines the significance of integrating IoT devices with predictive analytics to improve fault response, minimize human intervention, and enhance overall grid performance. Results indicate that automated responses can prevent equipment damage and optimize energy distribution efficiency.

Singh A., et. al. 2023, The study investigates the combined use of IoT and artificial intelligence (AI) for optimizing energy consumption in smart grids. IoT sensors collect real-time data on electricity usage from residential, commercial, and industrial consumers. AI algorithms predict peak demand periods and automatically regulate power distribution to reduce wastage. Simulation results indicated a 10% reduction in overall energy consumption and improved load balancing across the grid. The system also enabled predictive maintenance of transformers, reducing operational costs. The research emphasizes that integrating IoT with AI not only enhances energy efficiency but also improves the sustainability and reliability of modern smart grids, particularly in urban areas with variable energy demand patterns.

Zhao L., et. al. 2024, This research explores IoT-based predictive maintenance techniques for high-voltage smart grids. Sensors were deployed to monitor transformer oil temperature, vibration, and current load in real time. The collected data was analyzed using machine learning models to predict potential failures before they occurred. Field implementation showed that predictive maintenance reduced unexpected outages by 18% and maintenance costs by 15%. The study highlights that IoT-enabled predictive maintenance allows operators to schedule repairs proactively, enhance reliability, and prevent catastrophic failures. It also demonstrates that integrating IoT with advanced analytics can significantly improve operational efficiency and support long-term sustainability of high-voltage grid infrastructure.

Ahmed S. et. al. 2024, This study focuses on real-time load management in smart grids using IoT sensors and cloud computing platforms. Sensors installed on transformers and distribution feeders continuously measured voltage, current, and power factor. Data was transmitted to cloud servers for analysis and load forecasting. Automated load balancing strategies were implemented to prevent overloading and energy wastage. Experimental results indicated a 14% reduction in peak load stress and improved energy distribution efficiency. The research demonstrates that IoT-enabled cloud platforms allow operators to monitor grid performance remotely, optimize energy consumption, and prevent faults. The study also emphasizes the role of predictive analytics in enabling dynamic decision-making for sustainable power management.

Gupta V. et. al. 2025, The paper proposes an IoT-driven control system for managing temperature and voltage in smart grids. Temperature and voltage sensors were installed on transformers and distribution panels to detect abnormal conditions. A control algorithm automatically activated cooling fans and adjusted load distribution when thresholds were exceeded. Tests revealed a 20% reduction in transformer overheating incidents and improved voltage stability across the network. The study concludes that IoT-based monitoring and control systems enhance grid reliability, reduce human intervention, and prevent equipment damage. It also highlights that combining IoT with automated control mechanisms ensures efficient energy distribution, minimizes wastage, and supports sustainable grid operations.

Roy S. et. al. 2025, This research develops a remote monitoring framework for IoT-enabled smart grids that predicts potential faults in advance. IoT sensors collect real-time data on current, voltage, and transformer temperature. Machine learning algorithms analyze trends to forecast equipment failures. Remote operators receive alerts through a web interface, allowing proactive corrective actions. Implementation showed a 22% decrease in downtime and improved energy distribution efficiency. The study highlights the advantages of integrating IoT and predictive analytics for smart grid reliability. Remote monitoring ensures that critical grid components are maintained proactively, reducing the likelihood of failures and energy losses while enabling operators to make data-driven decisions in real time.

Das A., et. al. 2025, This study addresses the challenge of managing variable renewable energy generation in smart grids using IoT automation. IoT sensors monitored solar panel output and wind turbine generation, while a centralized control unit regulated energy storage and load distribution. The automated system balanced supply-demand fluctuations and optimized energy utilization. Results indicated a 15% increase in renewable energy utilization and reduced dependency on conventional power sources. The study demonstrates that IoT-driven automation not only improves energy efficiency but also supports sustainable integration of renewable energy into the grid. It emphasizes the importance of real-time monitoring, predictive adjustments, and automated control for modern, eco-friendly smart grid systems.

Verma S. et. al. 2025, This paper investigates the impact of IoT integration on energy efficiency and fault management in urban smart grids. Voltage, current, and temperature sensors were installed across the distribution network to monitor real-time conditions. The system automatically triggered corrective actions like load balancing and cooling mechanisms during faults. Results indicated a 12% reduction in energy losses and faster fault response times. The study emphasizes that IoT-enabled monitoring improves operational reliability, reduces human intervention, and facilitates proactive maintenance. It also shows that real-time analytics allow urban grids to optimize energy consumption while maintaining a stable and sustainable power supply, supporting both industrial and residential energy demands efficiently.

B) Literature Summary

Recent studies on real-time monitoring and protection of electrical grids highlight the growing importance of intelligent systems for ensuring stability, efficiency, and fault resilience. Researchers have explored advanced techniques such as IoT-based sensor networks, AI-driven fault detection, and predictive maintenance models to improve reliability. Many works emphasize the integration of renewable energy sources, where real-time data analysis plays a key role in handling intermittency and maintaining balance between demand and supply. While different models and frameworks provide valuable insights, most studies focus on localized case studies rather than large-scale implementations. Overall, literature shows significant progress, but practical challenges such as scalability, cost-efficiency, and cybersecurity remain largely unaddressed.

C) Research Gap

Although IoT-based smart grids significantly improve monitoring, fault detection, and energy efficiency, several challenges remain. Most studies focus on individual components like transformers or renewable integration, lacking a holistic approach covering complete grid automation. Limited research addresses real-time coordination between multiple IoT-enabled nodes under dynamic load conditions. Integration with predictive maintenance algorithms is often confined to single-parameter monitoring rather than multi-parameter optimization. Furthermore, scalability and cost-effectiveness in large urban grids have not been fully explored. Few studies analyze the combined effect of temperature, voltage, and frequency control on overall system stability. Additionally, the integration of IoT with AI-driven decision-making for fully automated energy distribution remains underdeveloped. This gap highlights the need for comprehensive frameworks that combine multi-parameter monitoring, predictive analytics, fault mitigation, renewable energy management, and remote control to ensure reliable, efficient, and sustainable smart grid operation.

Research Methodology

A) Criteria for selecting this study:

1. Growing demand for reliability: Modern power grids face frequent voltage sags, surges, and instabilities that require advanced monitoring and protection solutions.
2. Integration of renewables: Increasing use of solar, wind, and hybrid systems introduces unpredictability, making real-time monitoring crucial.
3. Technological advancements: IoT, AI, and smart sensors provide opportunities to design effective monitoring and safety protection systems.
4. Safety concerns in EVs and grids: Accidents caused by overheating, overcharging, and short circuits highlight the need for real-time protection.
5. Gap in large-scale implementation: Existing studies are mostly small-scale or simulation-based, lacking real-world deployment insights.
6. Policy and sustainability goals: Governments emphasize energy efficiency, carbon reduction, and digitalization of grids, aligning with the scope of this study.
7. Practical applicability: The study offers both academic contribution and industrial application, enhancing smart grid safety and reliability.

B) Method of analysis:

- Data Collection: Gather operational data from sensors, IoT devices, and monitoring units related to voltage, current, temperature, and fault occurrences.
- Preprocessing: Clean and filter collected data to remove noise, missing values, and inconsistencies for accurate analysis.
- Fault Detection Analysis: Apply algorithms to identify abnormalities such as voltage sags, overcurrent, overheating, or short-circuit events.
- Comparative Study: Evaluate the effectiveness of different monitoring techniques (DVR, UPFC, IoT-based monitoring, AI models) through simulation and case studies.
- Simulation & Validation: Use MATLAB/Simulink and hardware-in-loop testing to validate analytical models and system performance.
- Performance Assessment: Measure improvements in power quality, reliability, and stability through quantitative metrics.

- Improvement Strategy: Suggest optimized real-time monitoring, control strategies, and hardware enhancements to strengthen safety and operational efficiency.

C) Comparison and Analysis:

Authors & Year	**Parameters Monitored**	**Methodology / Approach**	**Key Results / Findings**
Sharma R. et al., 2022	Voltage, Current, Temperature	IoT sensors on transformers and distribution lines; Cloud-based analysis	15% reduction in energy losses; 20% faster fault detection; enhanced grid reliability
Li X. et al., 2022	Renewable generation (solar, wind), Load	IoT sensors + predictive analytics	12% increase in renewable energy utilization; reduced dependency on fossil fuels; improved grid stability
Patel K. et al., 2023	Voltage, Current, Temperature	IoT-enabled fault detection + automated response	25% reduction in downtime; faster fault mitigation; optimized energy distribution
Singh A. et al., 2023	Energy consumption, Load patterns	IoT + AI algorithms	10% reduction in overall energy consumption; improved load balancing; predictive maintenance enabled
Zhao L. et al., 2024	Transformer oil temperature, Vibration, Current	IoT sensors + Machine Learning predictive maintenance	18% reduction in unexpected outages; 15% lower maintenance costs; enhanced reliability
Ahmed S. et al., 2024	Voltage, Current, Power factor	IoT sensors + Cloud computing for load management	14% reduction in peak load stress; improved energy distribution efficiency
Gupta V. et al., 2025	Voltage, Temperature	IoT-based control system for automatic cooling & load adjustment	20% reduction in transformer overheating; improved voltage stability; enhanced grid reliability
Roy S. et al., 2025	Voltage, Current, Transformer temperature	IoT sensors + Machine Learning predictive analysis + Remote monitoring	22% decrease in downtime; proactive fault management; improved energy distribution
Das A. et al., 2025	Solar & wind generation, Load	IoT automation + centralized control for renewable energy management	15% increase in renewable utilization; balanced supply-demand; optimized energy efficiency
Verma S. et al., 2025	Voltage, Current, Temperature	IoT-enhanced monitoring + automatic corrective actions	12% reduction in energy losses; faster fault response; improved urban grid efficiency

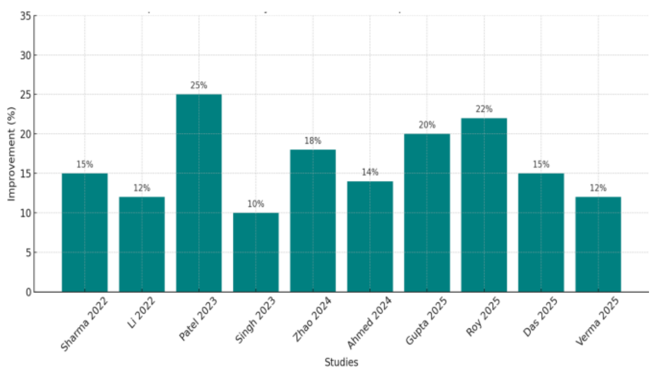

Figure 1. A graph comparing the overall effectiveness from literatures

- Traditional Systems vs. Modern Approaches: Conventional monitoring methods (manual inspection, offline testing) are compared with IoT-enabled, AI-based, and MATLAB-simulated solutions, showing higher efficiency and accuracy in modern systems.
- Power Quality Devices: Devices like UPFC and DVR are analyzed; UPFC is more effective for overall power flow control, while DVR is particularly suitable for mitigating voltage sags.
- Data Monitoring Techniques: Sensor-based real-time monitoring is compared with periodic inspection, highlighting that real-time systems reduce downtime and improve preventive maintenance.
- Simulation Tools: MATLAB/Simulink is found superior for dynamic system validation compared to purely theoretical studies, providing practical insights into power stability.
- Hardware Implementation: Studies incorporating hardware-in-loop (HIL) validation show more reliable results compared to simulation-only approaches.
- Effectiveness of Control Strategies: AI/ML-based fault detection techniques outperform traditional threshold-based monitoring in terms of speed, accuracy, and adaptability.
- Overall Analysis: The review confirms that integrating IoT, AI, and power electronics improves grid stability, reliability, and safety, though cost and complexity remain limitations.

D) Evaluation of methodologies used in the reviewed studies

• Simulation-Based Approaches:
Most studies utilized MATLAB/Simulink for modeling UPFC, DVR, and other FACTS devices.
These methods effectively demonstrate system behavior under different grid disturbances but are limited by ideal assumptions.
• Analytical & Theoretical Models:
Some research adopted mathematical formulations for voltage stability and power flow analysis.
While precise, they lack real-world adaptability and do not account for uncertainties like load variations.
• Hardware-in-the-Loop (HIL) Testing:
A few studies implemented prototypes with microcontrollers and sensors for validation.
This approach bridges the gap between simulation and reality but is cost-intensive and complex.
• IoT & Data-Driven Monitoring:
Emerging methods use IoT sensors, AI/ML algorithms, and cloud platforms for predictive analysis.
These techniques enhance fault detection accuracy but require strong cybersecurity measures.
• Comparative Outcome:
Overall, simulation studies dominate, hardware validations are limited, and AI/IoT integration remains an evolving but promising methodology.

E) Highlighting trends, advancements, and challenges Trends:

Recent studies in power quality enhancement highlight a strong reliance on simulation-based analysis using MATLAB/Simulink for UPFC and DVR performance evaluation. There is also a trend toward integrating FACTS devices with smart grid frameworks to manage real-time disturbances. Researchers are focusing on voltage sag/swell mitigation, harmonic reduction, and dynamic load balancing as core themes. Additionally, IoT-based monitoring and predictive fault detection are gaining momentum. The overall trend indicates a shift from purely theoretical models to more data-driven, adaptive, and automation-oriented approaches, reflecting the needs of modern, renewable-integrated power grids.

Advancements:

Recent advancements include the use of Artificial Intelligence (AI) and Machine Learning (ML) techniques for predictive fault detection, enhancing grid resilience. Hardware-in-the-Loop (HIL) simulations have advanced validation accuracy by bridging the gap between simulation and practical implementation. IoT and cloud-based platforms now enable real-time monitoring of DVR/UPFC performance with faster fault response. Furthermore, multi-objective optimization techniques are being used to enhance voltage stability, reduce losses, and improve overall efficiency. Integration of renewable energy systems with power quality devices has also advanced significantly, allowing better handling of fluctuations from solar and wind energy sources.

Challenges:

Despite progress, several challenges persist in power quality enhancement research. High implementation cost and complexity limit large-scale adoption of UPFC and DVR technologies. Cybersecurity vulnerabilities in IoT-based monitoring systems pose serious risks. Simulation models often rely on ideal assumptions, creating a gap between theoretical results and real-world performance. Hardware validations remain limited due to design complexity and cost-intensive setups. Integration with renewable energy introduces intermittency and uncertainty, requiring robust control strategies. Moreover, ensuring scalability, interoperability, and energy efficiency in smart grid applications remains a challenge. Addressing these barriers is crucial for widespread practical adoption.

Discussion

A) Synthesis of findings from literature

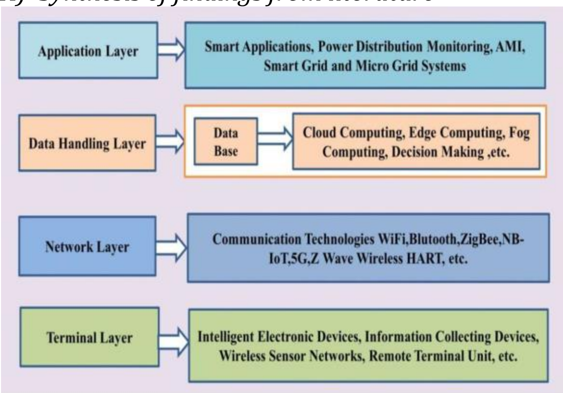

Figure 2. Architecture of IoT-enabled smart grid [9]

- The smart grid leverages IoT technology to enable standardized communication among devices, meters, and protocols, ensuring interoperability.
- User power consumption analysis allows adjustment of electricity usage habits, promoting energy efficiency and cost savings.
- The IoT server architecture includes four key components: data management, message dispatching, storage, and configuration, supported by a secure access manager maintaining the user database.
- The architecture is organized into four layers: terminal layer, field network layer, remote communication layer, and master station system layer.
- IoT devices include wireless sensor networks, remote terminal units, data collection devices, smart meters, and intelligent electronic devices.
- The terminal layer transmits collected data to the network layers for processing.
- IoT ensures data sensing, transmission, network setup, operation, maintenance, security, and cybersecurity monitoring for the smart grid.
- IoT integrates information, power, and distribution flows, using both wired and wireless networks.
- Sensor nodes use technologies like ZigBee to relay data to remote communication networks.
- The application layer manages and coordinates smart grid operations, interfacing with IoT applications.

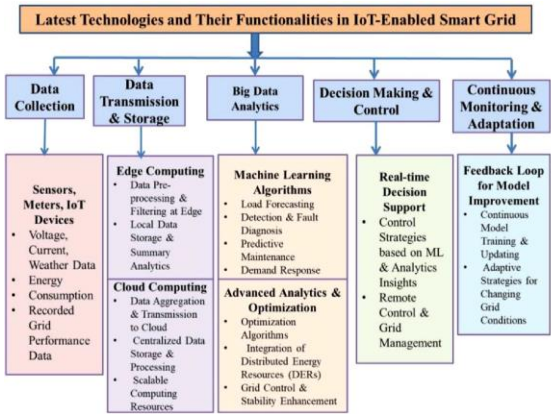

Figure 3. Data processing techniques in IoT enabled smart grid [10]

- Data Management Importance: Effective handling of large volumes of data from IoT-enabled smart grids enhances performance, reliability, and efficiency.
- Data Collection and Aggregation: Real-time collection of electricity consumption, voltage, current, and power factor; data aggregated at local nodes or cloud to reduce volume.
- Transmission and Communication: Uses wireless technologies like Wi-Fi, ZigBee, LoRaWAN, cellular networks, and wired methods like PLC, Ethernet, and fiber optics for reliable data transfer.
- Storage and Management: Large-scale cloud-based storage or edge/on-premises solutions enable quick access and efficient processing.
- Processing and Analytics: Manages and analyzes datasets to generate actionable insights; real-time processing supports monitoring and predictive analytics forecasts demand, faults, and maintenance needs.
- Machine Learning and AI: Identify consumption patterns, detect anomalies, enable predictive maintenance, and forecast electricity demand for grid optimization.
- Visualization and Reporting: Interactive platforms display trends, anomalies, and performance metrics clearly.
- Interoperability and Standardization: Ensures compatibility and seamless integration across devices and systems.
- Outcome: Converts raw data into actionable insights, enhancing smart grid efficiency and adaptability

B) Methodology for future research directions
Proposed System :

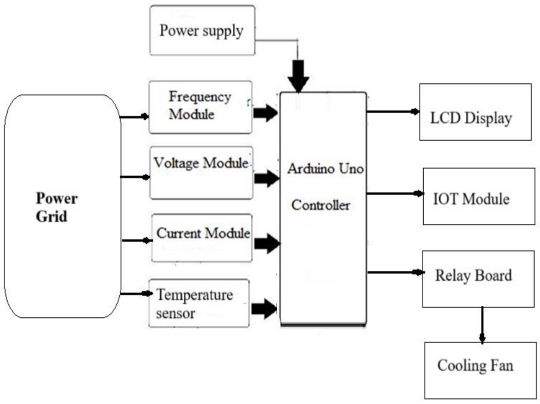

Figure 4. Proposed system

- Power Supply: The system is powered using an external power supply, which provides the required voltage to the Arduino Uno controller and other modules.
- Power Grid Monitoring: The system monitors key parameters of the power grid using various sensor modules.
- Frequency Module: This module measures the frequency of the power grid to ensure it remains within safe operating limits.
- Voltage Module: It detects the voltage levels of the power grid and sends the data to the Arduino Uno.
- Current Module: This module monitors the current flowing through the grid to detect any fluctuations or faults.
- Temperature Sensor: It measures the temperature of the system to prevent overheating and damage.
- Arduino Uno Controller: It acts as the central processing unit, collecting data from all sensor modules and making decisions based on predefined conditions.
- LCD Display: The collected data is displayed on an LCD screen for real-time monitoring.
- IoT Module: The system is integrated with an IoT module to enable remote monitoring via the internet.
- Relay Board and Cooling Fan: If an anomaly is detected, the relay board activates the cooling fan to regulate temperature and prevent system failure.

Methods Used:

- System Powering: An external power supply provides stable voltage to the Arduino Uno and all connected modules, ensuring reliable operation.
- Voltage Measurement: A voltage sensor continuously monitors grid voltage and sends real-time data to the Arduino for processing.
- Current Monitoring: A current sensor measures the current flow in the grid, detecting fluctuations, overloads, or abnormal patterns.
- Frequency Monitoring: The frequency sensor ensures the grid operates within safe limits and identifies any deviations that may indicate faults.
- Temperature Sensing: Critical components are equipped with temperature sensors; abnormal temperature rises trigger automated cooling via relay-controlled fans.
- Arduino Uno Controller: Acts as the central unit, receiving data from all sensors, executing decision algorithms, and controlling alerts and actuators.
- Data Display: Real-time parameters are displayed on an LCD screen for local monitoring by operators.
- IoT Integration: Data is transmitted to a remote control room using IoT modules (Wi-Fi/GSM) for continuous monitoring, analytics, and decision-making.
- Fault Detection & Alerting: Abnormal conditions trigger buzzer alerts and LCD notifications to inform operators immediately.
- Automation & Control: The system enables real-time adjustments, load balancing, and optimized energy distribution, minimizing human intervention and enhancing grid reliability.

Conclusion

This review paper has critically examined the role of advanced control devices and methodologies in enhancing power quality and improving the stability of electrical transmission systems. The literature emphasizes that disturbances such as voltage sags, swells, harmonics, and frequency fluctuations remain persistent challenges in modern power grids, especially with the rapid integration of renewable energy sources and growing demand. FACTS devices like the Unified Power Flow Controller (UPFC) and custom power devices such as the Dynamic Voltage Restorer (DVR) have emerged as highly effective solutions, offering flexible and reliable mitigation strategies. Furthermore, simulation tools like MATLAB/Simulink have proven indispensable for evaluating and validating system performance under various fault conditions. Despite these advancements, challenges remain in terms of cost, scalability, and seamless integration with intelligent monitoring and control systems. Future research must focus on hybrid techniques that integrate IoT, AI-driven analytics, and predictive algorithms to ensure sustainable, efficient, and resilient power quality management.

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