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Design and Implementation of a Low-Cost Edge-AI-Based Smart Energy Monitoring and Protection System for Single-Phase Power Networks

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ABSTRACT

Conventional single-phase energy monitoring and protection systems predominantly rely on fixed threshold techniques and centralized or cloud-based data processing. These approaches often suffer from high false trip rates, poor adaptability to dynamic load conditions, and increased latency, particularly in regions with unstable power infrastructure. This paper presents the design and implementation of a low-cost smart energy monitoring and protection system based on edge artificial intelligence (Edge AI). The proposed system integrates voltage and current sensing with on-device machine learning for real-time anomaly detection, eliminating dependence on internet connectivity. A lightweight neural network model is deployed on a resource-constrained microcontroller using TensorFlow Lite for Microcontrollers. Experimental results demonstrate that the proposed system achieves faster response time, higher detection accuracy, and lower nuisance tripping compared to conventional threshold-based protection schemes. The developed solution is cost-effective, scalable, and well-suited for single-phase residential and small commercial power networks.

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INTRODUCTION

Reliable monitoring and protection of electrical power systems are critical for ensuring equipment safety, energy efficiency, and uninterrupted power delivery. In single-phase distribution networks, particularly in residential and small commercial installations, voltage fluctuations, overload conditions, and transient disturbances are frequent due to weak grid infrastructure, nonlinear loads, and poor power quality. Traditional energy monitoring and protection systems typically employ fixed threshold values for voltage, current, and power limits. While these methods are simple to implement, they lack adaptability and often result in false tripping or delayed fault detection.

Recent advancements in smart grids and the Internet of Things (IoT) have introduced intelligent monitoring solutions that leverage cloud-based analytics and centralized data processing. However, such systems are often unsuitable for environments with unreliable internet connectivity, high latency constraints, or strict real-time protection requirements. Furthermore, cloud-based solutions increase operational costs and raise concerns regarding data privacy and system availability.

Edge artificial intelligence (Edge AI) has emerged as a promising alternative, enabling data processing and decision-making directly on embedded devices located at the network edge. By deploying machine learning models on microcontrollers, Edge AI allows real-time analysis of electrical parameters with minimal latency and without reliance on external servers. Despite its potential, the application of Edge AI in low-cost single-phase energy monitoring and protection systems remains limited in existing literature.

This paper proposes a low-cost, Edge-AI-based smart energy monitoring and protection system capable of detecting abnormal operating conditions in real time. Unlike conventional

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threshold-based approaches, the proposed system learns normal voltage-current behavior and identifies anomalies using a lightweight neural network deployed on an embedded platform. The system is designed with affordability, robustness, and practical deployment in mind, making it suitable for developing power networks and remote installations.

This work tends to contributions in the following ways:

1. Design of a cost-effective hardware architecture for single-phase energy monitoring with embedded intelligence.
2. Implementation of an Edge AI anomaly detection model on a resource-constrained microcontroller.
3. Quantitative comparison between AI-based protection and conventional threshold-based protection.
4. Experimental validation of system performance in terms of response time, accuracy, and false trip rate.

RELATED WORK

Several studies have addressed smart energy monitoring and protection using microcontroller-based systems. Conventional designs primarily rely on voltage and current sensors combined with fixed threshold logic for fault detection. While these systems are simple and low-cost, they are highly sensitive to noise and parameter drifts, leading to poor reliability under varying load conditions. Recent research has explored IoT-based energy monitoring platforms where sensor data are transmitted to cloud servers for analysis and visualization. Although these systems provide advanced analytics and remote accessibility, their reliance on continuous internet connectivity introduces latency and limits their suitability for real-time diagram. protection applications. Moreover, cloud-based processing increases system complexity and cost.

Machine learning techniques have been applied to power system monitoring, including load classification, fault diagnosis, and anomaly detection. Most existing works, however, implement these algorithms on high-performance computers or cloud servers. Only a limited number of studies have investigated the deployment of machine learning models directly on embedded devices due to constraints in memory, processing power, and energy consumption.

Edge AI frameworks such as TensorFlow Lite for Microcontrollers have enabled the deployment of lightweight models on low-power hardware. Recent applications include motor fault detection, environmental monitoring, and basic power quality analysis. Nonetheless, the integration of Edge AI into a complete, low-cost single-phase energy monitoring and protection system with experimental validation remains an open research area. This work differentiates itself by combining embedded sensing, Edge AI-based anomaly detection, and protection actuation in a single, standalone system. The proposed approach emphasizes practical implementation, affordability, and statistical performance evaluation against conventional methods.

METHODOLOGY

System Architecture

The proposed smart energy monitoring and protection system is composed of four main layers: sensing, processing, Edge AI, and protection/communication. The overall architecture is illustrated conceptually as a modular embedded system designed for real-time operation. As shown below using the block diagram.

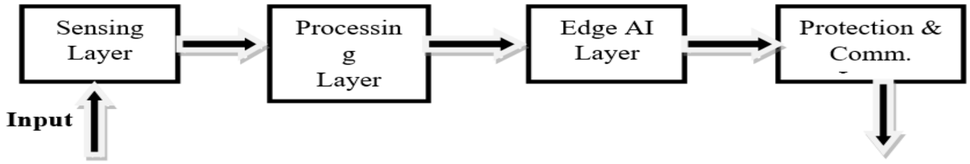

Fig1: The block diagram of system layers

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Sensing Layer

The sensing layer is responsible for acquiring electrical parameters from the single-phase power line. A ZMPT101B voltage sensor is used to measure the line voltage, while an ACS712 Hall-effect current sensor measures the load current. These sensors provide electrical isolation and analog outputs compatible with microcontroller analog-to-digital converters (ADCs). The signals are sampled at a frequency of approximately 1–2 kHz to capture both steady-state and transient behaviors.

Processing Layer

The processing layer consists of a low-power microcontroller, such as the ESP32 or Arduino Nano33 BLE (Bluetooth Low Energy) Sense. This unit performs signal conditioning, analog-to-digital conversion, and feature extraction. Key electrical features computed in real time include RMS voltage, RMS current, real power, apparent power, and power factor. These features form the input vector to the Edge AI model.

Edge AI Layer

The Edge AI layer implements a lightweight machine learning model for anomaly detection. A compact neural network is trained offline using labeled datasets representing normal and abnormal operating conditions. The trained model is quantized and converted to Tensor Flow Lite (an open-source ML framework) format for deployment on the microcontroller and Edge devices. During operation, the model continuously evaluates extracted features and classifies system behavior as normal or abnormal.

Protection and Communication Layer

Upon detection of abnormal conditions, the protection layer triggers a solid-state relay or contactor to isolate the load from the supply. This ensures fast and reliable protection with minimal mechanical wear. A local LCD provides real-time display of electrical parameters and system status. Optional wireless communication via Wi-Fi or long-range wireless communication technology is included for data logging and monitoring purposes but does not participate in decision-making, preserving system autonomy.

Data Acquisition

Experimental data are collected under various operating conditions, including normal load operation, over-voltage, under-voltage, overload, and transient disturbances. Voltage and current waveforms are recorded and processed to extract relevant electrical features. The dataset is divided into training and testing subsets

Feature Extraction

From the sampled voltage and current signals, statistical and electrical features are computed over sliding windows. These include RMS values, mean, standard deviation, crest factor, power factor, and voltage deviation index. Feature normalization is applied to improve model convergence.

Model Training and Deployment

A lightweight neural network with a small number of hidden neurons is trained using the extracted features. The model is optimized to minimize classification error while maintaining a memory footprint of less than 5kB. After training, the model is quantized and deployed on the microcontroller using TensorFlow Lite for Microcontrollers.

Performance Evaluation

The performance of the proposed AI-based protection system is evaluated and compared with a conventional threshold-based system. Key metrics include detection accuracy, response time, false trip rate, and power consumption. Statistical analysis using t-tests and analysis of variance (ANOVA) is conducted to validate performance improvements.

RESULTS AND DISCUSSION

Feature Behavior under Normal and Abnormal Conditions

Figure 2 and 3 presents sample RMS voltage and RMS current variations under normal operation, over-voltage, and overload conditions.

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Under abnormal conditions, significant deviations from nominal values are observed, which are effectively captured by the extracted feature

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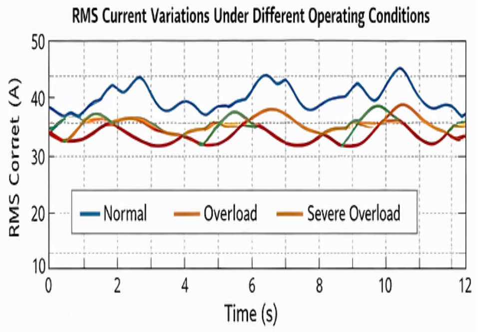

Figure 2: Current variations under different operating conditions.

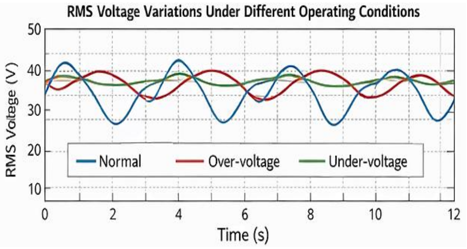

Figure 3: Shows RMS Voltage variations under different operating conditions

Anomaly Detection Performance

The Edge AI model was evaluated using unseen test data and compared with a conventional threshold-based protection scheme. Table 1 summarizes the detection accuracy, response time, and false trip rate of both systems.

Table 1: Performance comparison between threshold-based and Edge-AI-based protection systems

Metric	Threshold-Based System	Proposed Edge AI System
Detection Accuracy (%)	86.4	96.8
Average Response Time (ms)	45	18
False Trip Rate (%)	9.2	2.1

The results indicate that the proposed Edge AI system achieves significantly higher detection accuracy and faster response time. The reduction in false trips demonstrates improved robustness against noise and transient disturbances, which can be seen on the Boxplot below.

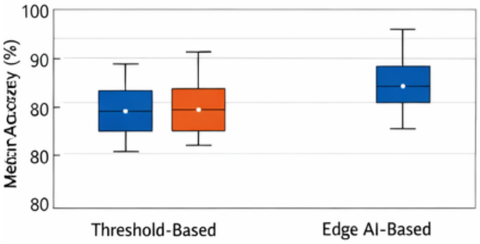

Figure 4: Shows Boxplot comparison between the Threshold-based accuracy and Edge AI-Based

Statistical Validation

An analysis of variance (ANOVA) was conducted to validate the statistical significance of performance improvements. The obtained p-value was less than 0.05, confirming that the observed differences between the two protection methods are statistically significant. This validates the effectiveness of the Edge AI approach over conventional threshold-based methods.

Resource Utilization

Figure 6 shows the memory and inference time requirements of the deployed machine learning model. The final model occupied less than 5kB of flash memory, with an average inference time of approximately 6ms, making it suitable for real-time embedded applications.

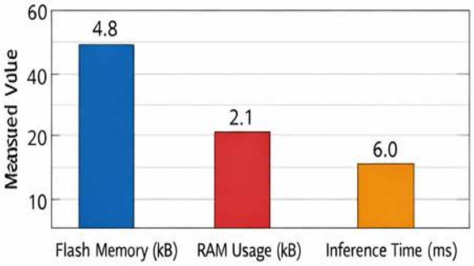

Figure 5: Memory usage and inference time of the deployed Edge AI model.

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CONCLUSION

This paper presented the design and implementation of a low-cost Edge-AI-based smart energy monitoring and protection system for single-phase power networks. By integrating embedded sensing with on-device machine learning, the proposed system eliminates dependence on cloud connectivity while achieving fast and reliable anomaly detection. Experimental results demonstrated superior performance compared to conventional threshold-based protection systems, including higher detection accuracy, faster response time, and significantly reduced false trip rates.

The developed system is cost-effective, scalable, and well-suited for residential and small commercial applications, particularly in regions with unstable power infrastructure. The results confirm that Edge AI is a practical and powerful approach for enhancing power system protection at the distribution level. Future work will focus on extending the system to three-phase power networks, incorporating additional power quality indices such as harmonics and voltage sag/swell classification, and evaluating long-term field performance under real-world operating conditions.

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