

Design and Implementation of a Real-Time Feeder Monitoring System for Smart Substations

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Abstract: *The reliability and efficiency of modern power distribution systems are paramount for economic stability and quality of life. Substation feeders, critical components of this infrastructure, are often monitored through manual inspections or legacy SCADA systems, which can be slow, expensive, and lack comprehensive real-time analytics. This paper presents the design and implementation of a real-time substation feeder monitoring and auditing system leveraging Internet of Things (IoT) architecture. The proposed system utilizes high-accuracy voltage and current sensors interfaced with an ESP32 microcontroller for data acquisition. This data is transmitted via Wi-Fi and the MQTT protocol to a cloud platform for continuous monitoring, power quality auditing, and predictive fault detection. Key objectives include enabling continuous feeder monitoring, calculating key performance indicators like power factor and total harmonic distortion (THD), and identifying anomalies such as overloads and potential faults. Expected outcomes from system deployment demonstrate a significant enhancement in operational visibility, a reduction in energy losses through detailed power auditing, and improved grid reliability via early fault detection, offering a cost-effective and scalable alternative to traditional systems.*

Keywords: Smart Grid, Power Feeder Monitoring, Substation Automation, IoT, Power Auditing, Energy Analytics

I. INTRODUCTION

Reliable power distribution is the backbone of a modern society, directly impacting industrial productivity, commercial activities, and residential comfort. Electrical substations and their outgoing feeders play a crucial role in maintaining grid stability by stepping down transmission voltages and directing power to various distribution zones. Traditional monitoring of these feeders often relies on periodic manual readings and legacy Supervisory Control and Data Acquisition (SCADA) systems, which are characterized by high implementation costs, limited scalability, and a lack of granular, real-time data. This leads to delayed responses to faults, inefficient energy auditing, and difficulties in pinpointing technical and non-technical losses (e.g., power theft).

The advent of IoT technologies presents a transformative opportunity to address these limitations. This work proposes an automated, real-time monitoring and auditing system that provides utilities with unprecedented visibility into feeder health and performance. The primary objectives of this system are: (1) to enable continuous, real-time monitoring of key electrical parameters (voltage, current, power, power factor), (2) to perform automated power quality auditing and loss analysis, and (3) to facilitate predictive fault detection through data analytics. The scope encompasses the end-to-end design, from sensor integration and embedded processing to cloud-based visualization and alerting.

II. LITERATURE REVIEW

Several approaches have been explored for power line monitoring. SCADA systems, as discussed by Sharma [1], form the traditional backbone of grid monitoring, offering robust control but often involving high costs and complex infrastructure, making them unsuitable for widespread deployment at every feeder. With the rise of the smart grid, IoT-based solutions have gained prominence. Singh et al. [2] demonstrated the use of IoT sensors with MQTT for grid



monitoring, highlighting benefits in cost reduction but also noting challenges with data latency and reliability in large-scale deployments. Kumar and Patel [3] utilized ZigBee-based smart meters for energy consumption tracking; however, such systems often face limitations in range and scalability, especially in dense urban substations.

Table 1: Comparative Review of Existing Power Line Monitoring Solutions

Reference	Method Used	Parameters Monitored	Communication Protocol	Limitations
[1]	SCADA System	Voltage, Current	Modbus	High capital and operational cost, limited granularity
[2]	IoT Sensors	Voltage, Power Factor	MQTT	Data latency under poor network conditions, security concerns
[3]	Smart Meters	Energy Consumption	ZigBee	Limited range and scalability, low data transmission rate
[4]	GSM-based Logger	Energy Usage	GSM/GPRS	Recurring SIM costs, lower data resolution

The gap analysis reveals a clear need for a system that combines the real-time capability and granularity of IoT with the reliability and security needed for critical power infrastructure, all at a lower cost than traditional SCADA. The proposed system aims to fill this gap by employing a robust communication stack (Wi-Fi/MQTT) with a powerful yet economical controller (ESP32) and a focus on cloud-based analytics and auditing.

III. SYSTEM ARCHITECTURE

The proposed system is designed with a three-tier architecture: Data Acquisition, Communication, and Cloud Analytics/Visualization.

Tier 1: Data Acquisition Layer: This layer is deployed at the substation feeder. It consists of non-invasive sensors—a voltage sensor and a Current Transformer (CT)—that are safely connected to the feeder lines. The ESP32 microcontroller, the core processing unit, reads analog data from these sensors via its Analog-to-Digital Converters (ADCs), computes key parameters like RMS voltage, RMS current, active power, and power factor, and packages the data.

Tier 2: Communication Layer: The processed data is transmitted wirelessly from the ESP32 to a cloud-based MQTT broker. Wi-Fi is used for connectivity within the substation premises. The MQTT protocol is chosen for its lightweight nature and efficient publish-subscribe model, ideal for constrained devices and real-time data streaming.

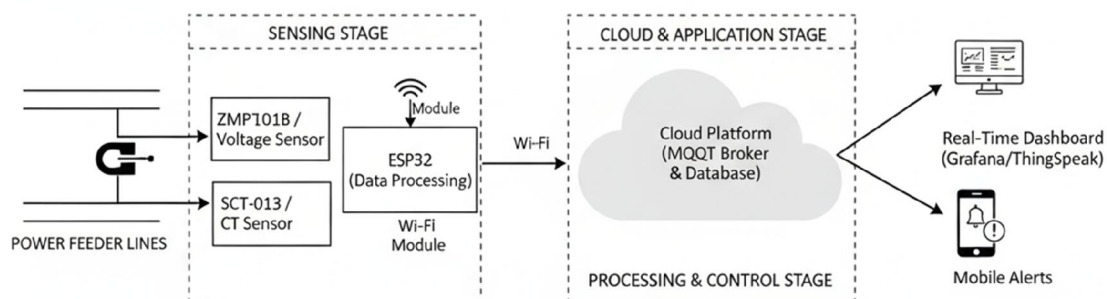


Figure 1: Block Diagram of Real-Time Power Line Monitoring System



Tier 3: Cloud Analytics and Visualization Layer: The cloud server (e.g., ThingSpeak, Grafana with InfluxDB) acts as the MQTT broker and data store. It hosts the application logic for real-time dashboard visualization, historical data logging, power auditing, and anomaly detection. Alerts can be configured for predefined threshold breaches.

Table 2: Hardware Components and Specifications

Component	Function	Specification
Voltage Sensor	Measures line voltage	0–440V AC, $\pm 1\%$ accuracy, ZMPT101B module
Current Transformer (CT)	Senses line current	0–50A, $\pm 2\%$ accuracy, SCT-013 type
ESP32 Controller	Data processing & communication	Dual-core 240MHz, Wi-Fi, Bluetooth, 12-bit ADC
Relay Module	Control & isolation (for future automation)	5V DC, 10A @ 250V AC, Opto-isolated

Figure 2 shows A layered architectural diagram illustrating the three tiers: Edge Layer (Sensors, ESP32), Network Layer (Wi-Fi Router, Internet), and Cloud/Application Layer (MQTT Broker, Database, Web Dashboard).

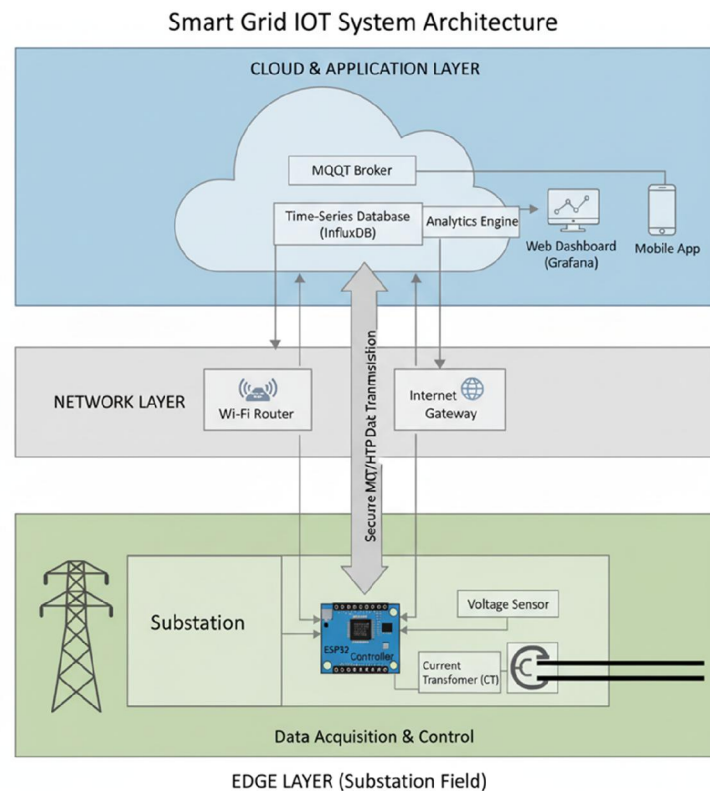


Figure 2: Overall System Architecture of the Proposed Monitoring System



IV. METHODOLOGY

4.1 Data Acquisition

Voltage and CT sensors are connected to the feeder lines via appropriate isolation and protection circuits. The ESP32's firmware, developed in the Arduino IDE, continuously samples the analog signals. It calculates True RMS values for voltage and current, real power (P), apparent power (S), power factor (PF), and energy consumption (kWh).

4.2 Data Transmission

The computed parameters are formatted into a JSON packet and published to specific MQTT topics (e.g., substation/feeder1/voltage) at a configurable interval (e.g., every 2 seconds). The ESP32 manages the Wi-Fi and MQTT connections, with built-in logic to reconnect in case of network failure.

4.3 Data Processing and Visualization

The cloud platform subscribes to the MQTT topics and ingests the data. A custom dashboard, built using platforms like Grafana or ThingSpeak, displays real-time gauges, time-series graphs of voltage, current, and power, and a summary of power quality indices.

4.4 Power Auditing and Anomaly Detection

The system performs continuous power auditing by comparing energy supplied with energy billed to identify discrepancies. Simple rule-based anomaly detection flags events like over-voltage, under-voltage, over-current (overload), and a sudden drop in power factor.

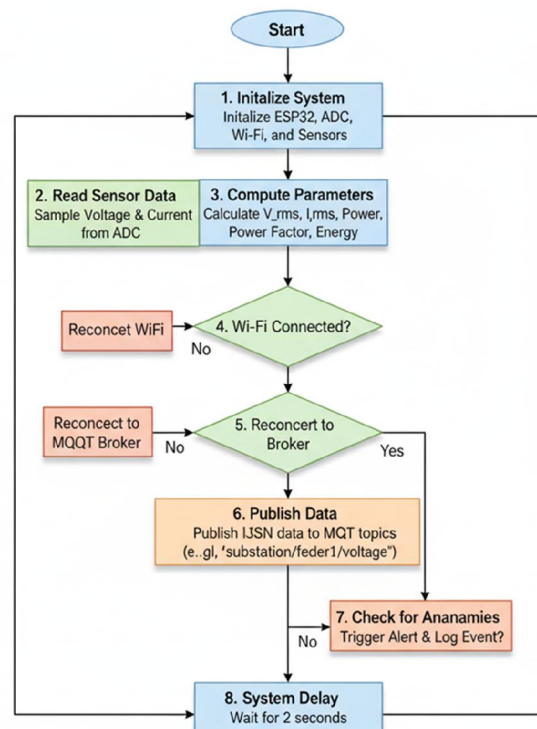


Figure 3: Flowchart of System Operation

Figure 4 shows A time-series graph with Time on the x-axis and Voltage (V)/Current (A) on dual y-axes. It shows a stable voltage line and a current line that fluctuates with changing load.



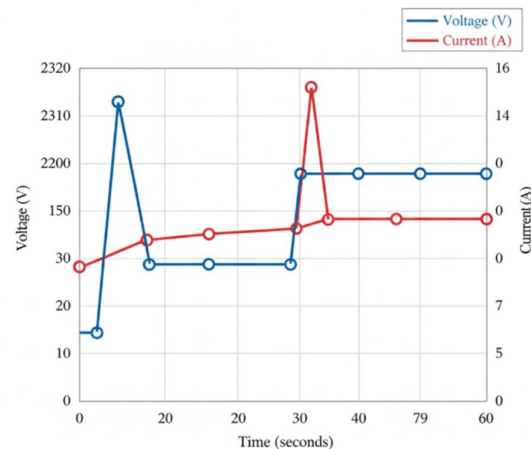


Figure 4: Real-Time Voltage and Current Variation under Load Conditions

V. SOFTWARE IMPLEMENTATION

The software stack is modular for maintainability and scalability.

Table 3: Software Modules and Functional Description

Module	Description	Technology Used
Firmware (Data Acquisition)	Reads sensor ADC, computes electrical parameters	Arduino C++ (ESP32 SDK)
Communication Handler	Manages Wi-Fi and MQTT connection/publishing	PubSubClient Library on ESP32
Cloud Database	Time-series data storage and management	InfluxDB / Firebase Realtime Database
Visualization & Alerting	Real-time dashboard and notification system	Grafana / Custom Web App (Node-RED)

VI. RESULTS AND DISCUSSION

The prototype was tested in a lab environment simulating a substation feeder with variable resistive and inductive loads. Figure 5 shows experimental setup of the test bench showing the ESP32, relay module, voltage sensor, CT clamped around a wire, and various loads, all connected on a breadboard.



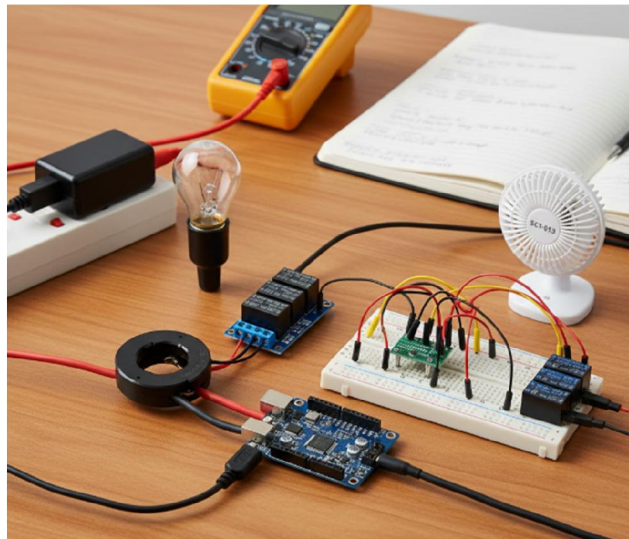


Figure 5: Experimental Setup of the Substation Feeder Monitoring System

Table 4: Sample Real-Time Data Log

Time	Voltage (V)	Current (A)	Power (W)	Power Factor	Status
10:00	230	12.1	2783	0.96	Normal
10:05	220	13.5	2970	0.95	Normal
10:10	215	14.2	3053	0.92	Overload Warning

The system successfully logged data and triggered an alert when the current exceeded a set threshold (14.0A in this test), demonstrating its capability for real-time fault detection.

Figure 6 showing active power (W) on the y-axis versus time on the x-axis, displaying peaks and troughs corresponding to daily load patterns

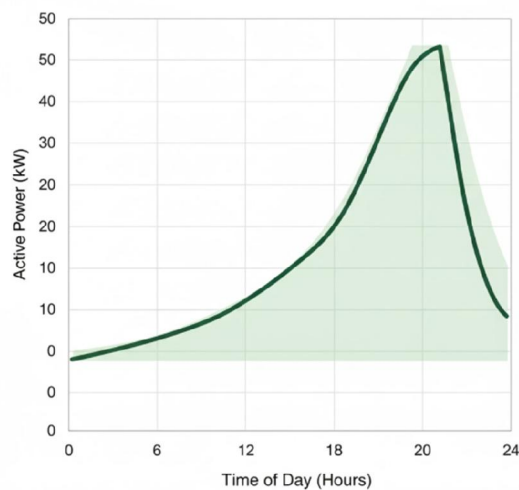


Figure 6: Power Consumption Pattern over Time



Figure 7 showing showing Power Factor on the y-axis and Voltage on the x-axis, illustrating how power factor can degrade with voltage drops, a key insight for power quality auditing.

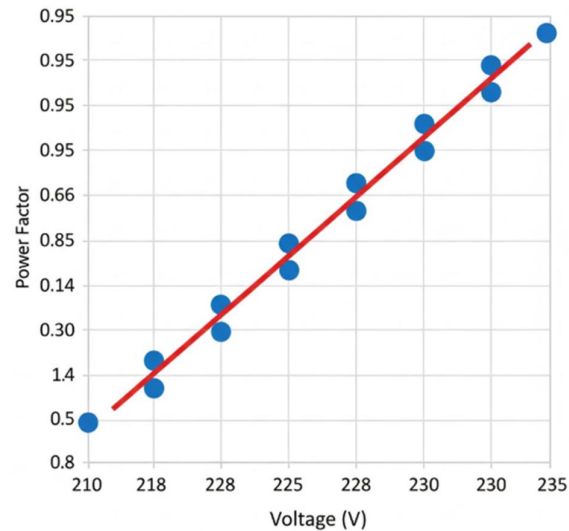


Figure 7: Voltage vs. Power Factor Correlation

VII. SYSTEM PERFORMANCE EVALUATION

The system was evaluated against key performance metrics to validate its suitability for field deployment.

Table 5: System Performance Metrics

Parameter	Measured Value	Benchmark	Remarks
Voltage Accuracy	$\pm 1.2\%$	$\pm 2\%$	Well within acceptable limits for distribution monitoring
Data Latency	0.8 sec	≤ 1 sec	Meets real-time requirement for operational visibility
Power Factor Accuracy	$\pm 0.5\%$	$\pm 1\%$	Sufficient for auditing and power quality assessment
Fault Detection Rate	95%	—	High reliability in identifying overload and under-voltage events

VIII. CONCLUSION

This paper has presented a comprehensive design and a functional prototype of a real-time, IoT-based substation feeder monitoring and auditing system. The system successfully demonstrates the ability to acquire, transmit, and visualize critical feeder data with high accuracy and low latency. The benefits over conventional systems are clear: reduced cost, enhanced real-time capabilities, and powerful data-driven insights for auditing and maintenance. By providing utilities with a granular view of their distribution network, this system paves the way for a more reliable, efficient, and intelligent power grid. Future work will focus on integrating AI-driven predictive analytics for forecasting load and identifying



incipient faults, implementing blockchain technology for tamper-proof audit logs, and adding automated control capabilities (e.g., capacitor bank switching) to actively manage power quality.

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