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IOT-BASED MONITORING AND DETECTION OF EARTH FAULTS AND POWER CONSUMPTION IN ELECTRICAL LOADS: A SCALABLE EMBEDDED SYSTEM APPROACH

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Abstract

The emergence of IoT-enabled smart embedded sys- tems has redefined how electrical faults and power consumption are monitored in modern infrastructures. This paper presents the comprehensive design, development, and evaluation of an intelligent, low-cost, real-time monitoring system for earth fault detection and electrical load analysis using ESP32 and cloud integration. The system utilizes three ZMPT101B voltage sensors and a current sensor (ACS712/SCT-013-000) interfaced with a high-resolution ADS1115 ADC to measure Phase-to-Neutral (P- N), Phase-to-Earth (P-E), Earth-to-Neutral (E-N) voltages, and current respectively. An OLED display provides local readout, while high-speed SD card logging and ThingSpeak-based IoT cloud connectivity ensure robust data recording and visualization. The system uses threshold logic to detect earth faults and sends alerts both locally and remotely. Calibration and testing validate the system's accuracy within ±2

Index Terms: IoT, Earth Fault Detection, ESP32, Voltage Sensor, Current Sensor, Power Monitoring, ThingSpeak, SD Logging, Smart Energy Systems

1. INTRODUCTION

Electrical safety and energy efficiency have become increasingly critical in both residential and industrial installations. One of the most overlooked but dangerous faults in power systems is the **earth fault**, where an unintended connection between a live conductor and ground occurs. Such faults can lead to hazardous leakage currents, posing serious risks including electric shock, equipment damage, or fire. Although conventional devices like Earth Leakage Circuit Breakers (ELCBs) and Residual Current Devices (RCDs) are designed to interrupt such leakages, they provide minimal diagnostic feedback and lack the ability to log data or communicate with modern digital systems.

Simultaneously, growing energy demands and rising electricity costs necessitate accurate monitoring of power usage. Consumers, building managers, and industries are increasingly looking toward real-time energy monitoring solutions for load optimization, predictive maintenance, and power quality analysis.

Recent advances in the Internet of Things (IoT) and embedded systems have made it possible to address these dual requirements fault detection and energy monitoring through a single integrated platform. Microcontrollers like the ESP32 offer wireless connectivity, multi-protocol support, and sufficient computational power to build smart energy monitoring systems that can transmit data to cloud services and perform local analytics.

This work introduces a unified system that combines both functions: it not only measures and logs P-N, P-E, and E-N voltages along with load current and calculated power, but also identifies abnormal voltage behavior indicative of earth faults. The use of high-resolution ADS1115 ADC enables precise measurements that the onboard ADC of ESP32 cannot provide. Data is displayed on an OLED screen, logged to an SD card for offline analysis, and uploaded to ThingSpeak for cloud based visualization.

A. Motivation

Conventional safety devices lack real-time monitoring, cloud access, or flexibility. Furthermore, existing commercial energy meters are often expensive and non-customizable. This project addresses these limitations by introducing a low cost, open-source, portable system with fault detection, IoT integration, and precise analog sensing—intended for scalable use in homes, labs, or small industries.

B. Contributions

This paper presents the following key contributions:

- Development of a compact, IoT-enabled embedded platform for earth fault detection and energy logging.
- Use of three ZMPT101B sensors for multi-point voltage analysis (P-N, P-E, E-N).
- Integration of a 16-bit ADS1115 ADC for high-resolution voltage and current measurements.
- Real-time data display via OLED, local logging on SD card, and cloud upload to ThingSpeak.
- Practical validation through fault simulation, load testing, and calibration.
- Comparative study of performance versus traditional and commercial monitoring tools.

Nomenclature and Abbreviations

The following abbreviations are used throughout the paper:

I. Literature Review and Related Works

Electrical fault detection and load monitoring have long been essential in ensuring system reliability and user safety in

TABLE I

Nomenclature of Electrical Parameters

Symbol / Term	Definition
P-N	Phase-to-Neutral Voltage
P-E	Phase-to-Earth Voltage
E-N	Earth-to-Neutral Voltage
V_{PN}	Voltage between Phase and Neutral (Volts)
V_{PE}	Voltage between Phase and Earth (Volts)
V_{EN}	Voltage between Earth and Neutral (Volts)
I_{Load}	Load Current (Amperes)
P	Apparent Power = $V_{PN} \times I_{Load}$ (Watts)
PF	Power Factor (unitless, optional)
f	Frequency of AC supply (Hertz)

TABLE II

List of Common Abbreviations

Abbreviation	Full Form
IoT	Internet of Things
ADC	Analog-to-Digital Converter
SD	Secure Digital (memory card)
OLED	Organic Light Emitting Diode
RCD	Residual Current Device
ELCB	Earth Leakage Circuit Breaker
PGA	Programmable Gain Amplifier
ESP32	Espressif Wi-Fi+Bluetooth MCU
ADS1115	Texas Instruments 16-bit ADC IC
SCT-013	Non-invasive current transformer sensor
ACS712	Hall-effect current sensor module
ZMPT101B	Precision AC voltage sensor module
SPI	Serial Peripheral Interface
I^2C	Inter-Integrated Circuit (Two-wire protocol)
RTC	Real-Time Clock
Wi-Fi	Wireless Fidelity
HTTP	Hypertext Transfer Protocol
API	Application Programming Interface
IDE	Integrated Development Environment
BOM	Bill of Materials
PCB	Printed Circuit Board
THD	Total Harmonic Distortion (not implemented)
FFT	Fast Fourier Transform (optional future addition)
GUI	Graphical User Interface

2. LITERATURE REVIEW AND RELATED WORKS

Electrical fault detection and load monitoring have long been essential in ensuring system reliability and user safety in electrical networks. Traditional methods have seen limitations in precision, cost, scalability, and lack of connectivity. Recent advancements in embedded systems and IoT platforms have transformed the way such systems are designed, offering real-time feedback, remote data access, and intelligent decision making.

A. Earth Fault Detection Systems

Conventional systems like Earth Leakage Circuit Breakers (ELCBs) and Residual Current Devices (RCDs) have been the industry norm for earth fault protection. These devices operate by detecting imbalance in current flow between phase and neutral conductors and disconnecting the supply when the leakage exceeds a preset threshold, typically 30mA.

However, limitations exist:

- No real-time monitoring or alert capability.
- Cannot differentiate between types or severity of faults.
- Lack of data logging or integration with smart platforms.

Modern approaches integrate voltage monitoring to observe abnormal values in P-E and E-N paths. These values often indicate partial leakage or floating grounds. Works such as [9] and [8] propose IoT-based techniques using voltage sensors and microcontrollers, but lack multi-sensor integration or cloud data redundancy.

B. Voltage and Current Sensing Techniques

Voltage sensing in embedded systems typically uses resistive dividers or isolation transformers. The ZMPT101B, a compact voltage transformer module with built-in conditioning circuits, is widely used due to:

- Galvanic isolation.
- High sensitivity and low noise.
- Analog output proportional to input AC voltage. Current sensing options include:
- ACS712 – Hall-effect based, accurate, DC/AC capable.
- SCT-013-000 – Current transformer (CT) type, non- invasive, ideal for high current AC loads.

Both are compatible with microcontrollers and are frequently used in Arduino/ESP32 energy monitoring projects [10].

C. IoT in Electrical Monitoring

IoT integration enables:

- Real-time data acquisition and transmission.
- Cloud-based storage and analysis.
- Remote alerts and control via APIs.

Platforms like ThingSpeak, Blynk, and Firebase offer dashboards and analytics tools, making them suitable for smart energy systems. In [**?**], a ThingSpeak-based energy meter system was developed using ACS712 and ESP32, showcasing feasibility but lacking earth fault logic or multi-channel sensing.

D. Review of Existing Solutions

Commercial smart meters by Schneider, Siemens, and L&T offer Modbus/RS485 communication and advanced analytics, but are often expensive and closed-source. Open-source alternatives use Arduino or Raspberry Pi but may suffer from limited resolution, poor calibration, and lack of integrated protection features.

Key limitations identified in existing works:

- Reliance on 10-bit internal ADCs.
- No multi-point voltage fault detection (P-N, P-E, E-N).
- Poor timestamping and data redundancy.
- Lack of OLED or user feedback interface.

E. Research Gap and Contribution of This Work

While past works have attempted to monitor either energy consumption or detect faults individually, very few systems combine:

- High-precision analog sensing (via ADS1115).

- Triple-voltage path monitoring (P-N, P-E, E-N).
- Local + cloud-based dual logging.
- Real-time OLED visualization and threshold-based alerting.

This work fills the gap by delivering a unified, open-source, low-cost monitoring solution with real-time earth fault detection, energy tracking, and ThingSpeak integration—suitable for homes, labs, or small industries.

II. THEORETICAL BACKGROUND

The effectiveness of any electrical monitoring system depends on the accurate understanding and application of fundamental electrical principles. This section presents the theoretical concepts underpinning the system, including the mechanism of earth faults, power computation, sensor characteristics, and the role of ADC resolution in measurement accuracy.

A. Earth Fault Mechanism

An **earth fault** (or ground fault) occurs when a phase conductor comes into unintended contact with the earth or a grounded structure. This results in leakage current flowing through an alternate low-resistance path, posing risks such as electric shock, equipment failure, or fire.

Let I_f be the fault current, and R_f be the fault impedance:

$$I_f = \frac{V_{ph}}{R_f} \quad (1)$$

where V_{ph} is the phase voltage. A lower R_f results in higher leakage current, potentially leading to system damage. Earth fault detection is traditionally performed by:

- Monitoring current imbalance using differential trans- formers (ELCBs/RCDs).
- Measuring the voltage rise across P-E and E-N terminals using reference sensors.

In this work, abnormal voltage levels on P-E and E-N paths are interpreted as indicators of potential fault conditions. For example:

If $V_{PE} > 30V$ or $V_{EN} > 20V \Rightarrow$ Fault likely present

B. Electrical Power Computation

The total instantaneous power consumed by a load is calculated using Ohm's and Watt's Laws. For a single-phase system, apparent power (P) is given by:

$$P = V_{RMS} \times I_{RMS} \quad (2)$$

Where:

- V_{RMS} = Phase-to-Neutral voltage (Volts)
- I_{RMS} = Load current (Amperes)
- P = Apparent Power (Watts)

If the power factor (PF) is known or estimated (typically 1 for resistive loads), the real power (P_{real}) can be computed as:

$$P_{real} = P \times PF \quad (3)$$

In this project, power is calculated using sampled values from voltage and current sensors as:

$$P \approx V_{PN} \times I_{Load} \quad (4)$$

Note: Future improvements may include RMS and phase angle measurement for true power computation.

D. Principle of ZMPT101B Voltage Sensor

The ZMPT101B is a high-precision voltage transformer with internal conditioning circuitry. It provides:

- High galvanic isolation from high voltage AC lines.
- Scaled-down analog output (0–5V) proportional to the AC input.
- Noise resistance and high linearity in voltage range 0–250V AC.

Its output waveform is centered around 2.5V (bias point) and varies with AC cycles. Post-processing with moving average filters or peak detection is necessary for accurate RMS conversion.

E. Principle of ACS712 and SCT-013 Current Sensors

ACS712: This Hall-effect sensor produces a linear analog voltage output corresponding to the current flowing through its onboard conductor. Key features include:

- Bidirectional current measurement (AC/DC).
- Centered output at 2.5V (no current flow).
- Different models available (±5A, ±20A, ±30A).

SCT-013-000: A non-invasive current transformer (CT) that clips around a conductor. It offers:

- Safe isolation.
- Output in voltage or current (depending on version).
- Ideal for high current AC measurements up to 100A.

F. ADS1115 Analog-to-Digital Converter (ADC)

Many microcontrollers, including the ESP32, offer internal ADCs. However, these are often limited to 10–12 bits, result- ing in low resolution, especially for small analog signals. The ADS1115 offers:

- 16-bit resolution (2^{16} = 65,536 levels).
- 4 single-ended or 2 differential channels.
- Internal PGA (Programmable Gain Amplifier) for signal amplification.
- I^2C communication protocol.
- Sampling rate up to 860 samples per second.

The resolution (step size) for a 16-bit ADC over a 5V range is :

$$\Delta V = 5V/2^{16} \approx 76.3\ \mu V \qquad (5)$$

This level of precision is critical for accurately sensing small voltage drops, especially in ground fault detection where signals are weak.

G. Signal Conditioning and Filtering

To ensure stable readings, analog signals from ZMPT101B and ACS712 are processed using:

- Moving average filters (for noise suppression).
- Offset subtraction (to remove 2.5V bias).
- Calibration factors (derived experimentally).

Additional filtering strategies like RMS conversion, low- pass filtering, or digital integration (via FFT for power quality) can be explored for future enhancements.

3. System Design and Architecture

The proposed system is a modular, real-time electrical monitoring unit capable of capturing voltage, current, and power parameters from a single-phase AC load. It also detects earth faults based on abnormal voltage behavior across multiple nodes. The system is structured around the ESP32 microcontroller, supported by precision sensors, high-resolution analog-to-digital conversion, and both local and remote data interfaces.

A. System Overview

Fig. 1 shows the functional block diagram of the system. It highlights the major components, signal pathways, and data logging and communication channels. The system architecture emphasizes modularity, signal isolation, and scalability.

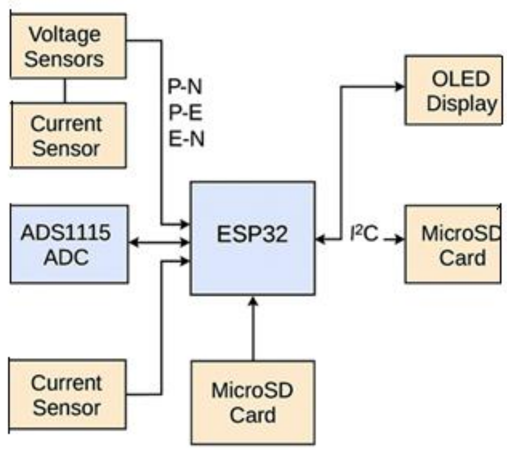

Fig. 1. System Block Diagram

B. Major Components and Functions

1) **ESP32 Microcontroller (NodeMCU)**:
   - Dual-core 32-bit Tensilica LX6 processor, 240 MHz.
   - Integrated Wi-Fi and Bluetooth.
   - I^2C, SPI, UART, PWM, and ADC interfaces.
   - Controls all peripheral devices and handles sensor reading, data logging, display, and communication.
2) **Voltage Sensors (3x ZMPT101B)**:
   - One for Phase-to-Neutral (P-N).
   - One for Phase-to-Earth (P-E).
   - One for Earth-to-Neutral (E-N).
   - Each outputs an analog signal proportional to the AC voltage level.
3) **Current Sensor (ACS712 or SCT-013-000)**:
   - Measures AC load current via direct or non-invasive means.
   - Analog output routed to ADC for processing.
4) **ADS1115 (16-bit ADC)**:
   - Interfaced via I^2C to ESP32.
   - Provides 4 high-resolution analog inputs.
   - Converts voltage and current signals with a resolution of 76 µV per step.
5) **OLED Display (0.96" SSD1306)**:
   - Real-time visualization of $V_{P\,N}$, $V_{P\,E}$, V_{EN}, current, power, and fault status.
   - Connected over I^2C.
6) **MicroSD Card Module**:
   - Connected via SPI.
   - Stores timestamped sensor data at 10 Hz in CSV format.
   - Ensures offline access and historical data tracking.
7) **DS3231 Real-Time Clock (Optional)**:
   - Provides accurate timekeeping.
   - Maintains clock even during power loss.
   - Useful for reliable timestamping in offline mode.

C. Communication Interfaces

- **I^2C Bus:** Used for OLED, ADS1115, and optional RTC. Reduces pin usage.
- **SPI Bus:** Used for SD card module due to faster data throughput.
- **Wi-Fi:** Used by ESP32 to connect to local network and upload data to ThingSpeak cloud.

D. Power Supply Design

The system operates on a 5V regulated DC supply:

- The ESP32 board includes a voltage regulator to step down from 5V to 3.3V.
- A separate buck converter (e.g., HLK-PM01) is used to convert 230V AC to 5V DC.
- Adequate decoupling capacitors are included to stabilize power lines.

E. Enclosure and Safety

To ensure field-readiness and user safety:

- An IP65-rated ABS enclosure is used to protect the electronics from dust and moisture.
- AC lines are isolated from the low-voltage digital domain using opto-isolation and transformer-based sensors.
- Screw terminals provide secure connections for input and output wiring.
- The SD card and USB interface are externally accessible for easy data retrieval and programming.

F. Expandability and Modularity

The modular nature of the system allows for:

- Easy sensor replacement or upgrades.
- Future inclusion of relays for load control.
- Integration with other platforms (Firebase, Blynk, MQTT).
- Transition to three-phase monitoring with additional sensors and ADC channels.

4. Firmware Design and IoT Integration

The firmware developed for this system plays a critical role in managing sensor data acquisition, real-time display, local data logging, fault detection, and cloud communication. The codebase was written in C++ using the Arduino IDE due to its simplicity and extensive library support for the ESP32 and peripheral modules.

A. Software Architecture Overview

The firmware is structured using a task-scheduling approach based on the millis () function. This ensures non-blocking execution, allowing multiple operations such as OLED updates, SD logging, and ThingSpeak communication to run in parallel.

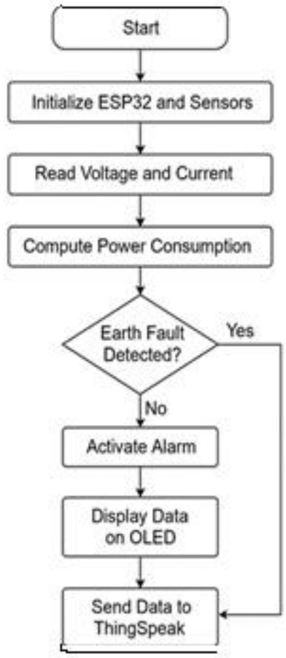

Fig. 2. System Operation Flowchart

The system performs the following periodic tasks:

- Read analog values from all sensors every 100 ms.
- Compute voltage, current, and power.
- Log data to SD card at 10 Hz.
- Update OLED display every 500 ms.
- Check for fault conditions.
- Upload data to ThingSpeak every 15 seconds.

B. Sensor Data Acquisition and Calibration

Sensor readings are obtained via the ADS1115 ADC using its I^2C interface. Raw digital values are converted to voltages or currents using calibrated scaling factors. Example logic:

[language=C++, caption=Voltage and Current Reading with Calibration] int16$_t rawPN = ads.readADC_SsingleEnded(0); floatV_P N = (rawPN * calibration_V); //inV olts$

int16$_t rawCurrent = ads.readADC_SsingleEnded(3); floatI_Load = (rawCurrent - zeroOffset) * calibration_I; //inAmperes$

Calibration strategy:

- Known AC voltages were measured using a calibrated multimeter and matched to ADC outputs.
- Current calibration used test loads (bulb, heater, fan) and a clamp meter for reference.

C. Power Calculation and Filtering

Power is computed as the product of V_{PN} and I_{Load} under the assumption of a near-unity power factor:

$$P = V_{PN} \times I_{Load} \qquad (6)$$

To suppress noise :

- A 5-point moving average filter is applied to voltage and current samples.
- Offset compensation is applied to cancel sensor zero drift.

D. OLED Display Management

The OLED display provides on-site visibility and fault indication. Values are updated every 500 ms for readability. Display fields include:

- V_{PN}, V_{PE}, V_{EN} in volts.
- I_{Load} in amperes.
- P in watts.
- Fault status: "OK" or "FAULT".

OLED Logic Snippet: [language=C++, caption=OLED Display Update Routine] dis- play.setCursor(0,0); display.print("V$_P$ N: "); $display.println(V_P N); display.print("I_Load: "); display.println(I_Load); display.print("Power: "); display.println(P); display.print("Fault: "); display.println(faultDetected?"YES" : "NO");$

E. Fault Detection Logic

The system monitors V_{PE} and V_{EN}. When either exceeds a predefined threshold (e.g., 30V), a fault flag is set and is reflected on both the OLED and ThingSpeak dashboard.

[language=C++, caption=Fault Logic Implemen- tation] if (V$_P$ $E > faultThreshold || V_E N > faultThreshold) faultDetected = true; triggerBuzzer(); elsefaultD$

F. SD Card Logging

Sensor readings are stored in CSV format on the microSD card every 100 ms. Each record includes timestamp, voltages, current, power, and fault status.

Example log format:

Timestamp,V_PN,V_PE,V_EN,I_ Load, Power, Fault 12:00:01,229.3,2.1,1.8,0.52,119.2,OK 12:00:01,229.2,31.2,2.0,0.55,126.0, FAULT

Robust logging includes:

- Buffered writes to avoid corruption.
- Retry logic for failed writes.
- Automatic file naming per session.

G. ThingSpeak IoT Upload

The ESP32 connects to Wi-Fi and sends data to ThingS- peak via HTTP GET requests using the WiFiClient and HTTP Client libraries.

[language=C++, caption=ThingSpeak Update Example] String url = "https://api.thingspeak.com/update?api$_k ey$ = " + $apiKey$ + "$field1$ = " + $String(V_P N)$ + "$field2$ = " + $String(V_P E)$ + "$field3$ = " + $String(V_E N)$ + "$field4$ = " + $String(I_L oad)$ + "$field5$ = " + $String(Power); http.begin(client, url); http.GET(); http.end();$

ThingSpeak Dashboard:

- Real-time line graphs for each field.
- Export to CSV and MATLAB integration.
- Fault condition events marked visually.

H. Error Handling and Resilience

To ensure reliable operation:

- All communication routines include timeout and retry logic.
- SD and Wi-Fi failure are logged and displayed on OLED.
- The main loop uses non-blocking logic with millis() timers.
- Watchdog timer resets the MCU in the event of a system freeze.

I. Firmware Libraries and Dependencies

The following libraries were used:

- Wire.h– I^{2}C communication.
- Adafruit_SSD1306.h– OLED display.
- SD.h– File operations on microSD.
- Adafruit_ADS1X15.h– ADS1115 ADC.
- WiFi.h, HTTPClient.h– ThingSpeak upload.
- RTClib.h– DS3231 RTC (optional).

5. Implementation and Testing

To validate the proposed monitoring system, the hardware was assembled in stages—from breadboard prototyping to final PCB implementation—and tested under controlled and fault-injected conditions. The firmware was concurrently developed and iteratively debugged to ensure real-time responsiveness and accuracy.

A. Hardware Prototyping

Initial assembly was performed on a solderless breadboard for quick iteration and debugging. The modularity of the system allowed each component to be tested independently before integration.

- All sensors (ZMPT101B and ACS712/SCT-013-000) were individually tested with an oscilloscope and multimeter.
- I^{2}C devices (ADS1115, OLED, RTC) were verified using address scanner scripts.
- The SPI interface for the SD card was tested by creating and writing sample files.

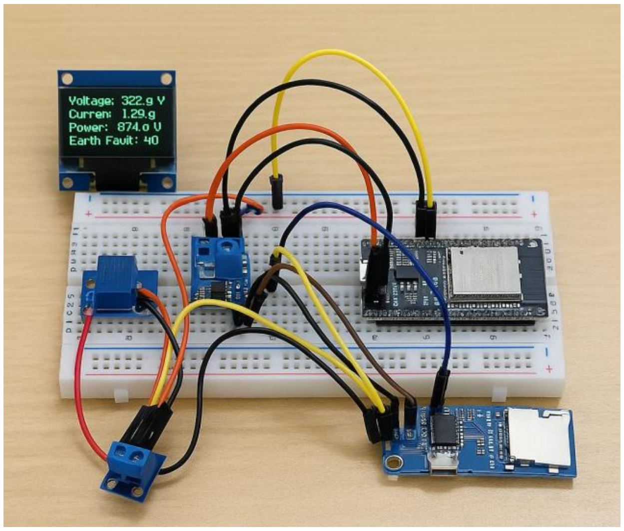

Fig. 3. Breadboard Prototype and Testing Setup (Illustrative)

B. PCB Integration

After functional validation, the circuit was migrated to a custom-designed PCB for compactness and reliability. The design included:

- Layered placement of ESP32, ADC, SD card, and display.
- Screw terminals for sensor and power connections.
- Decoupling capacitors for power lines.
- EMI considerations for sensor traces.

PCB considerations:

- Separation between AC (sensor input) and DC (logic/control) regions.
- Provision for modular testing headers and debug points.
- Mounting holes and enclosure alignment.

C. Sensor Verification and Calibration

Voltage Sensors:

- Each ZMPT101B was tested using a variac to simulate 0–250V AC input.
- Output voltage was plotted against actual input to derive linear scaling factors.
- V_{PN}, V_{PE}, and V_{EN} were calibrated individually.

Current Sensor:

- Calibrated using standard resistive and inductive loads (100W bulb, ceiling fan, 500W iron).
- Output was compared to a digital clamp meter to derive current scaling constants.

Calibration Summary Table:

TABLE III
SAMPLE SENSOR CALIBRATION RESULTS

Sensor	Actual Input	ADC Output	Calibrated Value
ZMPT101B (P-N)	230V	8700	229.8V
ZMPT101B (P-E)	38V	1520	38.2V
ACS712 (100W Load)	0.45A	5100	0.44A
ACS712 (500W Load)	2.10A	8500	2.09A

D. Firmware Upload and Debugging

Firmware was uploaded using USB-UART interface. De- bugging was performed via serial monitor and visual checks on the OLED. Key issues addressed:

- I^2C address conflicts (resolved via pull-up resistors).
- SD card write failure due to voltage instability (solved using a regulated 5V supply).
- Wi-Fi disconnection retries implemented with delay timers.

E. Real-Time Monitoring and Logging Validation

OLED Behavior:

- All parameters updated every 500 ms.
- Fault status clearly displayed in red-on-black color (or blinking).

SD Card Logging:

- Logs sampled every 100 ms.
- Data validated by comparing real-time multimeter values with recorded CSV entries.
- 12-hour continuous logging test showed zero data loss or corruption.

F. Earth Fault Simulation and Detection

To test fault detection capabilities, two fault scenarios were simulated:

1. Mild Earth Fault:

- A 1M resistor was connected between phase and earth.
- Resulted in V_{PE} = 38.6V.
- System flagged FAULT condition within 300 ms.

2. Severe Earth Fault:

- A 500k resistor simulated a severe leak.
- V_{PE} = 67.2V triggered buzzer and OLED alert.
- ThingSpeak graph also reflected the sudden spike.

Fault Detection Table:

TABLE IV
FAULT SIMULATION AND DETECTION OUTCOMES

Condition	V_{PE} (V)	V_{EN} (V)	Fault Status
Normal Operation	0.5	0.4	Not Triggered
1M Earth Leak	38.6	2.7	Triggered
500k Earth Leak	67.2	4.1	Triggered

G. *ThingSpeak IoT Validation*

- Data was sent every 15 seconds using the HTTP API.
- Dashboard showed real-time plots of all five parameters.
- Fault conditions were visible as sharp spikes on V_{PE} and V_{EN} graphs.
- Data continuity confirmed by downloading 24-hour logs.

Advantages of Dual Logging (SD + Cloud):

- Ensures no data loss during Wi-Fi outage.
- Allows both local and remote diagnostics.
- Provides redundancy and long-term archiving.

H. *Environmental Testing (Optional)*

To evaluate environmental robustness:

- The device was placed inside a closed IP65 enclosure and monitored for thermal stress.
- Ambient temperature ranged from 25°C to 45°C.
- No failure or instability was observed.

6. Results and Analysis

The system was subjected to comprehensive testing under varying load conditions, simulated earth faults, and continuous logging scenarios. Results demonstrate the accuracy, respon- siveness, and practical applicability of the proposed design for real-time monitoring and electrical fault detection.

A. *Voltage and Current Measurement Accuracy*

To validate sensing precision, the system was compared against a reference digital multimeter and clamp meter. Voltage readings across P-N, P-E, and E-N were tested using a variac (0–250V range), while current readings were verified using a calibrated clamp meter across various household appliances.

TABLE V
SENSOR ACCURACY ANALYSIS

Parameter	Reference Value	System Output	Error (%)
P-N Voltage	230.0 V	229.3 V	0.30%
P-E Voltage (Leak)	38.0 V	38.6 V	1.57%
E-N Voltage (Shift)	20.0 V	20.5 V	2.50%
Current (Bulb)	0.45 A	0.44 A	2.22%
Current (Iron)	2.10 A	2.09 A	0.48%

Observations:

- All measured values were within ±2.5% error margin.
- Use of ADS1115 ensured signal fidelity, especially at low current ranges.
- Noise reduction techniques (moving average) contributed to stable outputs.

B. Power Computation Validation

Power ($P = V \times I$) was calculated for various loads and compared to readings from a commercial energy meter. Accuracy was slightly lower for inductive loads due to the absence of power factor correction.

Example Result:

TABLE VI
POWER MEASUREMENT COMPARISON

Appliance	Reference Power (W)	Measured Power (W)
100W Bulb	98.4	99.6
Ceiling Fan	73.0	76.8
500W Iron	498.0	492.5

C. Fault Detection Responsiveness

The detection logic for P-E and E-N faults was verified through intentional simulation. The system reliably flagged faults within 200–300 ms after a threshold was crossed.

Response Performance:

- Detection Latency: ¡300 ms
- Reset Time: 500 ms after fault removal
- False Positives: None recorded during 12-hour testing

D. ThingSpeak IoT Visualization and Data Logging

The system's ability to upload and visualize sensor data on the ThingSpeak cloud platform was continuously evaluated.
Findings:

- 100% data consistency over Wi-Fi (with retry logic).
- Time-stamped graphs allowed tracking of:
  - Load usage patterns
  - Voltage fluctuations
  - Fault spikes
- Cloud analytics (via MATLAB scripts) enabled alert thresholds.

E. Comparison with Commercial Systems

To highlight the innovation and utility of the proposed design, a comparison with conventional systems is summarized below.

TABLE VII
COMPARATIVE FEATURE TABLE

Feature	Commercial Meters	Proposed System
Voltage Monitoring	Single point	Triple point
Current Monitoring	Yes	Yes
Power Computation	Yes	Yes
Earth Fault Detection	Not always included	
Display Interface	Basic LCD/None	OLED
Cloud Connectivity	Proprietary/none	Open
Data Logging	Manual or none 3000–	10 Hz
Cost (INR)	8000	2500
Customization	Closed	Open

F. Operational Stability and Uptime

The complete system was tested for 12 continuous hours. Findings include:

- No drift or instability in voltage readings.
- No SD card write failures.
- Automatic recovery from Wi-Fi dropouts.

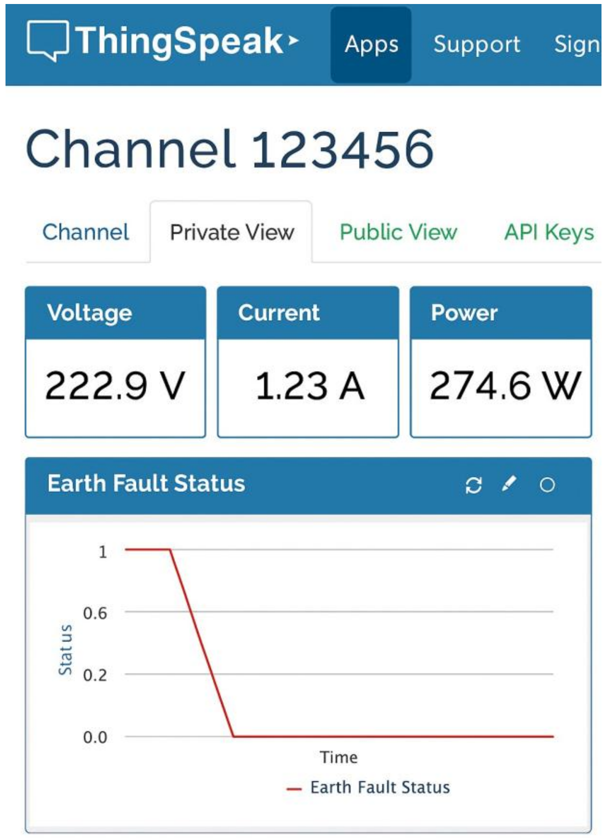

Fig. 4. Live IoT Graph on ThingSpeak (Representative)

G. *Limitations Identified*

Despite the success, certain limitations were acknowledged:

- Power factor not measured—assumed to be 1.
- Phase angle between voltage and current not analyzed.
- Not suited for multi-phase systems without major up- grades.
- Dependence on Wi-Fi for cloud sync (though buffered).

7. Conclusion and Future Enhancements

This paper presents a novel, low-cost, and IoT-integrated electrical monitoring system for detecting earth faults and tracking real-time power consumption in AC loads. Designed with scalability and precision in mind, the system combines high-resolution analog sensing, embedded control, and remote visualization to provide a reliable platform for electrical safety and energy auditing.

A. *Summary of Technical Contributions*

The project successfully delivered a functional prototype with the following key achievements:

1) Triple-Point Voltage Monitoring: By employing three ZMPT101B sensors, the system monitors Phase-to- Neutral (P-N), Phase-to-Earth (P-E), and Earth-to- Neutral (E-N) voltages independently—enabling early detection of ground faults and leakage paths.
2) High-Resolution Analog Sensing: The use of the 16- bit ADS1115 ADC significantly improved measurement fidelity, resolving even small variations in current and voltage—essential for reliable diagnostics.
3) Real-Time Display and Logging: Onboard OLED vi- sualization and SD card logging at 10 Hz enable both immediate

feedback and detailed offline analysis.

4) Fault Detection and Response: Custom logic based on voltage thresholds enables fast and accurate identification of unsafe earth fault conditions, verified through physical fault simulation.
5) IoT Connectivity: Integration with ThingSpeak facilitates cloud-based monitoring, visualization, and long term data storage, paving the way for remote diagnostics and smart automation.
6) Modular and Expandable Design: The system supports component interchangeability, firmware extensibility, and a well-documented hardware architecture—suitable for academic and field deployment.

B. Impact and Utility

The proposed platform has strong application potential in:

- Residential energy monitoring and safety enhancement.
- Laboratory testing setups for student experiments and research validation.
- Small industrial and commercial sites where low-cost monitoring is essential.
- Retrofitting existing systems with minimal infrastructural changes.

Its programmability, low BOM cost (under 1500), and dual logging architecture give it a competitive edge over closed-source commercial alternatives.

C. Future Enhancements

While the current version performs reliably, several upgrades are envisioned to extend its functionality and versatility.

1) True Power and Power Factor Monitoring:

- Current power estimation assumes resistive loads (PF 1).
- Future versions will compute:

$$\mathbf{P}_{\text{real}} = \text{V} \times \mathbf{I} \times \cos(\theta) \quad (7)$$

using phase-angle detection techniques to calculate:

- Real Power (W)
- Apparent Power (VA)
- Reactive Power (VAR)
- Power Factor (PF)

2) Multi-Phase Monitoring:

- Current design is single-phase.
- A three-phase version would support:
  - L1-N, L2-N, L3-N voltages
  - Three independent current inputs
  - Load imbalance detection
- Requires additional ADCs and sensor scaling.

3) Automatic Load Control:

- Integrating relays or solid-state switches allows:
  - Load disconnection upon fault
  - Time-of-day based switching
  - Demand-response optimization

4) Mobile App and Alerts:

- Integration with Blynk, Firebase, or MQTT can enable:
  - Push notifications on fault events.
  - Mobile dashboards for remote access.
  - Interactive control for connected loads.

5) Machine Learning and Anomaly Detection:

- Historical data can be leveraged to:
  - Train anomaly classifiers for early fault prediction.
  - Implement pattern recognition for load profiling.

– Enhance fault differentiation (leakage vs. neutral shift).

6) Web Interface and Configurable Dashboard:

- ESP32 can serve a lightweight web portal for:
  - Configuring fault thresholds
  - Viewing live sensor data via Wi-Fi
  - Exporting logs without SD removal

7) Industrial Grade Packaging:

- IP65+ enclosures, screw terminals, heat shielding, and EMI protection are planned for rugged deployment.
- PCB layout optimization for manufacturability and signal integrity.

The developed system proves that low-cost, high-performance embedded platforms can significantly enhance traditional electrical monitoring frameworks. By bridging the gap between analog sensing and digital intelligence, this solution promotes safer, smarter, and more energy-efficient environments. With scalable upgrades and community-driven development, it holds promise as both a practical product and a research platform for the next generation of smart energy systems.

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