A Cost-Effective IoT Framework for Real-Time Electrical Energy Monitoring and Web-based Visualization

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ABSTRACT

This paper presents the design and development of an ultra-compact, cost-effective smart energy monitoring framework utilizing the ESP32 Super Mini microcontroller (equipped with an OLED display) and the PZEM-004T module. While many existing solutions rely on heavy computational models or complex decentralized networks, the proposed system emphasizes accessibility and practical domestic deployment. It accurately measures critical electrical parameters—voltage, current, active power, energy consumption, frequency, and power factor—and synchronizes them instantaneously to a Firebase cloud database while displaying real-time status locally. A lightweight, web-based interface allows users to remotely track power usage and historical trends across any internet-connected device without requiring dedicated applications. Experimental benchmarking against commercial meters confirms the system's high precision, demonstrating its viability as an efficient, low-barrier solution for everyday household energy management.

Keywords

Internet of Things (IoT), Energy Monitoring System, Smart Energy Management, Real-Time Monitoring, Web-Based Monitoring

1. INTRODUCTION

In recent years, the rapid growth in electricity consumption across both residential and industrial sectors has significantly increased the demand for efficient and transparent energy management solutions. Traditional electromechanical and standard digital meters are generally limited to displaying the cumulative power usage. They lack detailed tracking, real-time data visualization, and remote management capabilities. Consequently, households and facility managers face considerable challenges in identifying abnormal consumption patterns, detecting inefficient appliances, and ultimately optimizing their energy efficiency. To address these limitations, the development of intelligent electrical energy monitoring systems has emerged as a crucial research focus within the broader context of smart homes and the Internet of Things (IoT).

The integration of IoT technology enables embedded computing devices to communicate seamlessly over the internet, facilitating real-time data acquisition, cloud storage, and remote supervision. By continuously measuring essential parameters, these smart systems provide users with actionable insights necessary for effective optimization and cost reduction. Previous studies have consistently highlighted the versatility of embedded platforms across various domains. For instance, IoT architectures have been successfully applied to develop automatic token counting machines for modern transportation systems [1]. Focusing specifically on residential energy, [2] developed an AI-IoT smart energy system for multi-unit buildings utilizing dual PZEM-004T sensors and LSTM models for hourly energy prediction. Embedded technologies also extend to urban infrastructure, enabling robust smartphone-based smart parking management systems [3]. Similarly, addressing comprehensive household utility tracking, [4] proposed an IoT-based system integrating multi-sensor data fusion to monitor both electricity and water consumption. Expanding further into environmental applications, wireless sensor networks have been utilized for remote online temperature monitoring of road structures [5]. Returning to the challenge of secure energy data, [6] introduced a monitoring system that combines ACS712 sensors with the InterPlanetary File System (IPFS) to guarantee decentralized storage and secure data sharing. These foundational works confirm that wireless connected devices offer highly reliable and scalable solutions for practical engineering challenges. To further contextualize our contribution, a comparative study with recent advancements is essential. Recent literature has extensively explored advanced metering infrastructures. For instance, Mohamed *et al.* [7] highlighted the integration of artificial neural networks for intelligent energy management, achieving high prediction accuracy but demanding substantial computational resources. Similarly, Mirani *et al.* [8] proposed an industrial IoT framework utilizing edge data processing, which, despite its robustness, presents a steep learning curve and high deployment costs for typical residential users. Furthermore, recent studies such as the IoT-enabled smart electricity meter developed by Garcés *et al.* [9] have emphasized the need for real-time energy efficiency, yet many of these solutions rely on complex multi-sensor architectures or proprietary ecosystems. Compared to these recent journal papers, our proposed system prioritizes immediate domestic accessibility and cost-effectiveness by completely bypassing heavy computational requirements and proprietary platforms, instead offering a lightweight, open-architected web dashboard.

While these recent studies introduce sophisticated methodologies such as machine learning forecasting and decentralized networks, they often require complex computational infrastructure, high implementation costs, and advanced technical expertise to deploy. For widespread domestic adoption, there remains a critical need for an ultra-compact, cost-effective, and highly accessible solution that prioritizes straightforward real-time visualization without the overhead of heavy processing models. Addressing this gap, this paper introduces the design and implementation of an accessible IoT-based electrical energy monitoring framework tailored for immediate household deployment. Unlike complex multi-sensor or AI-heavy architectures, the proposed system leverages the ultra-compact ESP32 Super Mini microcontroller, which features an integrated OLED display for immediate local status feedback, seamlessly integrated with a PZEM-004T sensor. This streamlined hardware setup captures a comprehensive set of electrical parameters and utilizes Firebase Realtime Database for instantaneous cloud synchronization. Furthermore, the system completely bypasses the need for dedicated mobile applications or local servers by employing a lightweight, custom-built web dashboard. The primary objective is to deliver a highly accurate, low-barrier monitoring framework that empowers end-users with practical, real-time energy transparency.

The remainder of this paper is organized as follows. Section II details the overall system design and methodology, encompassing the hardware architecture, embedded software configuration, cloud database integration, and the web-based monitoring interface. Section III presents the test scenarios and discusses the experimental results, including a comparative accuracy analysis against a commercial power meter. Finally, Section IV concludes the study and outlines potential future developments.

2. SYSTEM DESIGN AND METHODOLOGY

2.1 Overall System Architecture

The proposed monitoring system comprises four main components: the power supply, the measurement block, the cloud database, and the web interface, as illustrated in Fig. 1.

The power supply converts 220V AC to 5V DC to ensure stable operation for the control circuit. The PZEM-004T module measures parameters from a single-phase AC load and transmits them via UART to the ESP32 Super Mini. The microcontroller then displays this data locally on its OLED screen, processes it, and uploads it to the cloud database, making it accessible for the web application.

2.2 Hardware Design

Figure 2 shows the hardware schematic. The AC source connects to the load through the PZEM-004T and its corresponding current transformer (CT). An AC-DC converter steps down the voltage to power the ESP32 Super Mini.

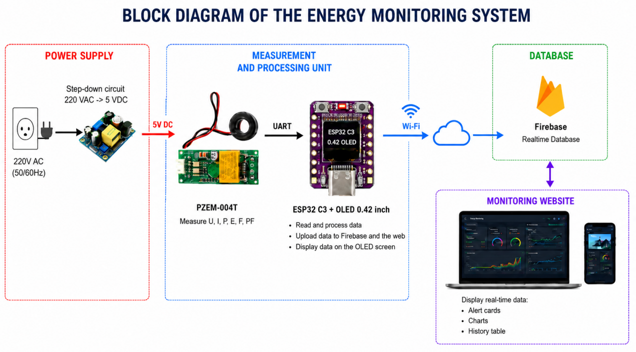


Fig. 1. System block diagram.

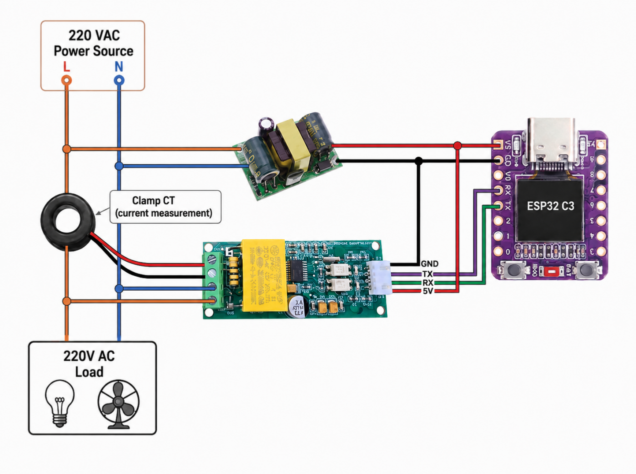


Fig. 2. Hardware connection diagram.

The ESP32 Super Mini was chosen for its compact form factor, integrated wireless capabilities, low power consumption, and its built-in OLED display, which allows users to monitor real-time system states and electrical parameters directly at the hardware level. The PZEM-004T provides accurate readings suitable for embedded applications. The assembled prototype is presented in Fig. 3, highlighting the microcontroller, sensor module, power supply, and CT sensor. Figure 4 depicts the operating structure of the PZEM-004T module by using V9881D Chip.

2.3 Embedded Software and Firebase Integration

Developed using the Arduino IDE, the firmware continuously polls the PZEM-004T. Active power is calculated as:

$$P = U \times I \times \cos\phi \tag{1}$$

where P is the active power, U is voltage, I is current, and $\cos\phi$ is the power factor. Figure 5 displays the network and authentication configuration in the ESP32 program.

During testing, the Arduino IDE's Serial Monitor is utilized as a primary debugging tool to verify the real-time acquisition of electrical parameters before they are transmitted to the cloud (Fig. 6). As illustrated, the ESP32 accurately reads the root-mean-square (RMS) voltage, current, active power, accumulated energy, grid frequency, and power factor directly from the PZEM-004T. Each

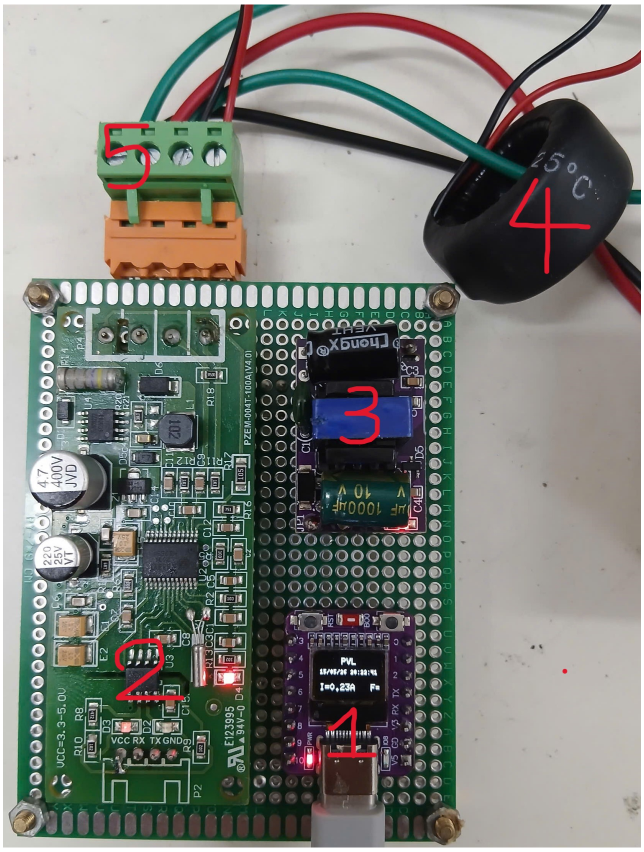


Fig. 3. Actual circuit after assembly.

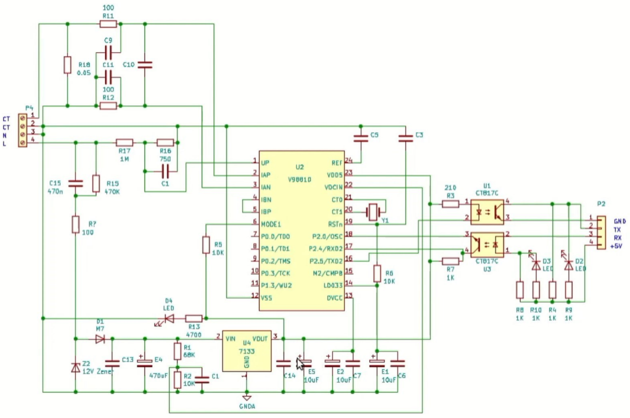
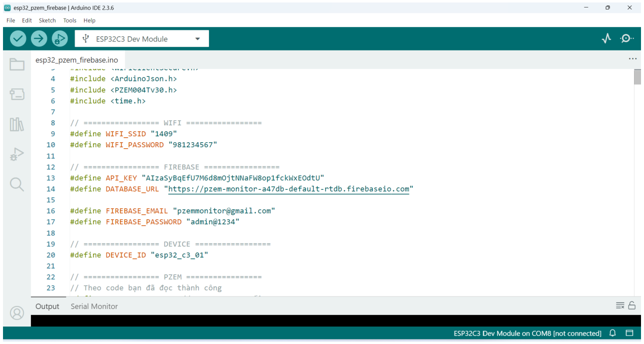


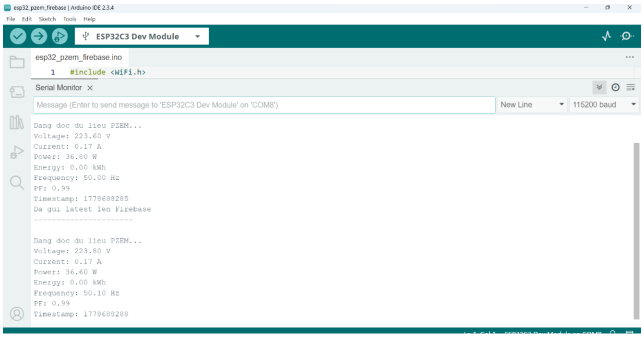
Fig. 4. Schematic structure of the PZEM-004T measurement module.

polling cycle also generates a unique UNIX timestamp to maintain temporal data integrity. Furthermore, the console outputs execution status messages—such as confirming successful transmission to the Firebase `latest` branch—ensuring that developers can closely track the synchronization flow. If the sensor becomes unresponsive or returns invalid readings, the microcontroller immediately flags the error and halts transmission to prevent logging corrupted data.



```
#include <ArduinoJson.h>
#include <PZEM004Tv30.h>
#include <time.h>

// ================= WIFI =================
#define WIFI_SSID "1409"
#define WIFI_PASSWORD "981234567"

// ================= FIREBASE =================
#define API_KEY "AIzaSyBqEfU7M6d8mOjtNNaFW8op1fckWxEOdtU"
#define DATABASE_URL "https://pzem-monitor-a47db-default-rtdb.firebaseio.com"

#define FIREBASE_EMAIL "pzemmonitor@gmail.com"
#define FIREBASE_PASSWORD "admin@1234"

// ================= DEVICE =================
#define DEVICE_ID "esp32_c3_01"

// ================= PZEM =================
// Theo code bạn đã đọc thành công
```

Fig. 5. Database and network configuration in the ESP32 firmware.

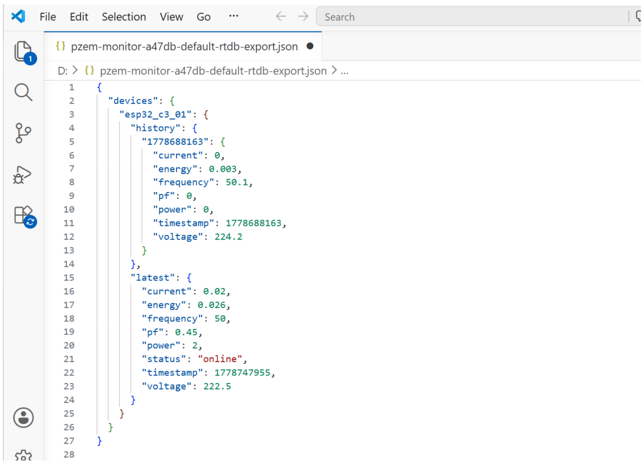


```
#include <WiFi.h>
```

```
Dang doc du lieu PZEM...
Voltage: 223.60 V
Current: 0.17 A
Power: 36.80 W
Energy: 0.00 kWh
Frequency: 50.00 Hz
PF: 0.99
Timestamp: 1778688285
Da gui latest len Firebase
----------------------

Dang doc du lieu PZEM...
Voltage: 223.80 V
Current: 0.17 A
Power: 36.60 W
Energy: 0.00 kWh
Frequency: 50.10 Hz
PF: 0.99
Timestamp: 1778688288
```

Fig. 6. Serial Monitor displaying acquired sensor data.

Firebase Realtime Database handles data synchronization. The cloud structure (Fig. 7) is divided into `latest` (for immediate UI updates) and `history` (for timestamped records). This architecture, alongside the synchronization flow shown in Fig. 8, guarantees low-latency data access and reliable storage.

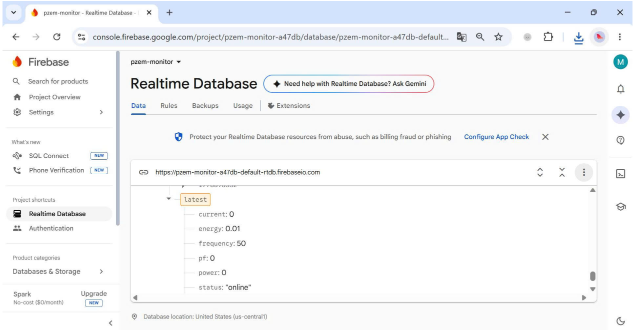


```
{
  "devices": {
    "esp32_c3_01": {
      "history": {
        "1778688163": {
          "current": 0,
          "energy": 0.003,
          "frequency": 50.1,
          "pf": 0,
          "power": 0,
          "timestamp": 1778688163,
          "voltage": 224.2
        }
      },
      "latest": {
        "current": 0.02,
        "energy": 0.026,
        "frequency": 50,
        "pf": 0.45,
        "power": 2,
        "status": "online",
        "timestamp": 1778747955,
        "voltage": 222.5
      }
    }
  }
}
```

Fig. 7. Data structure of the `latest` and `history` branches.

2.4 Web-Based Monitoring Interface

The dashboard, built with HTML, CSS, and JavaScript, fetches cloud data to dynamically render the user interface. The live mon-

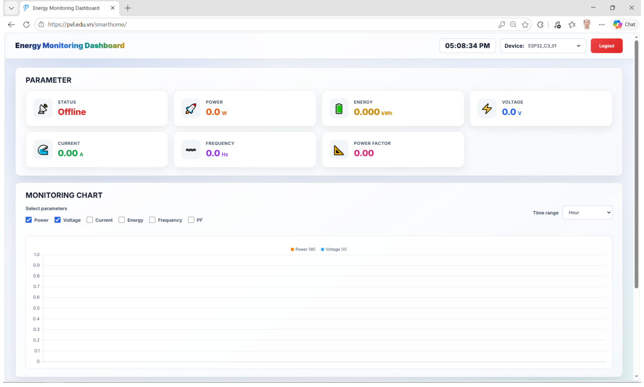


https://pzem-monitor-a47db-default-rtdb.firebaseio.com

```
latest
  current: 0
  energy: 0.01
  frequency: 50
  pf: 0
  power: 0
  status: "online"
```

Fig. 8. Data synchronization using Firebase.

itoring system is publicly accessible at `https://pvl.edu.vn/smarthome/`. It detects device connectivity; if transmission ceases for a defined threshold, the status switches to offline, and values are zeroed out to prevent displaying stale information.



05:08:34 PM
Device: ESP32_C3_01

STATUS Offline
POWER 0.0 W
ENERGY 0.000 kWh
VOLTAGE 0.0 V
CURRENT 0.00 A
FREQUENCY 0.0 Hz
POWER FACTOR 0.00

☑ Power ☑ Voltage ☐ Current ☐ Energy ☐ Frequency ☐ PF
Time range: Hour

Fig. 9. Web homepage displaying current electrical parameters.

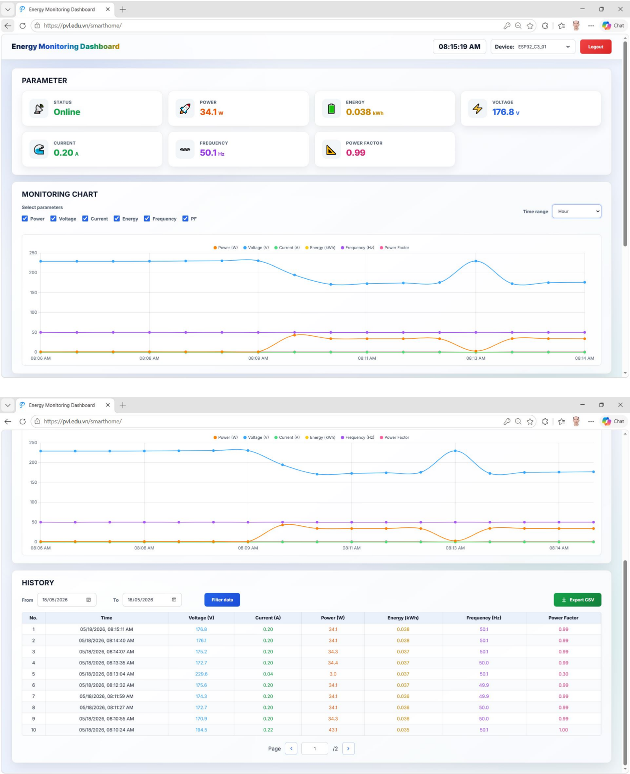
Figure 9 illustrates the homepage with real-time visual cards and dynamic charts. Furthermore, as presented in Fig. 10, the dashboard provides a comprehensive "History" module that enables users to query past system records with high granularity. By utilizing the built-in date pickers, users can filter historical data across specific timeframes, including days, months, and years. The queried results are displayed in a detailed paginated table and can be instantaneously exported as a CSV (Comma-Separated Values) file. This export functionality is highly advantageous for users needing to archive consumption data locally or perform deeper, long-term offline analyses.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Test Scenario

To validate system performance, the following test procedure was executed:

(1) Power the ESP32, measurement module, and an AC load.
(2) Verify network connection and sensor initialization.
(3) Confirm that sensor readings (voltage, current, power, energy, frequency, PF) are correctly logged to the cloud.
(4) Ensure the web interface dynamically updates based on the database.



08:15:19 AM
Device: ESP32_C3_01

STATUS Online
POWER 34.1 W
ENERGY 0.038 kWh
VOLTAGE 176.8 V
CURRENT 0.20 A
FREQUENCY 50.1 Hz
POWER FACTOR 0.99

☑ Power ☑ Voltage ☑ Current ☑ Energy ☑ Frequency ☑ PF
Time range: Hour

From 18/05/2026 To 18/05/2026

No.	Time	Voltage (V)	Current (A)	Power (W)	Energy (kWh)	Frequency (Hz)	Power Factor
1	05/18/2026, 08:15:11 AM	176.8	0.20	34.1	0.038	50.1	0.99
2	05/18/2026, 08:14:40 AM	176.1	0.20	34.1	0.038	50.1	0.99
3	05/18/2026, 08:14:07 AM	175.2	0.20	34.3	0.037	50.1	0.99
4	05/18/2026, 08:13:35 AM	172.7	0.20	34.4	0.037	50.0	0.99
5	05/18/2026, 08:13:04 AM	229.6	0.04	3.0	0.037	50.1	0.30
6	05/18/2026, 08:12:32 AM	175.6	0.20	34.1	0.037	49.9	0.99
7	05/18/2026, 08:11:59 AM	174.3	0.20	34.1	0.036	49.9	0.99
8	05/18/2026, 08:11:27 AM	172.7	0.20	34.1	0.036	50.0	0.99
9	05/18/2026, 08:10:55 AM	170.9	0.20	34.3	0.036	50.0	0.99
10	05/18/2026, 08:10:24 AM	194.5	0.22	43.1	0.035	50.1	1.00

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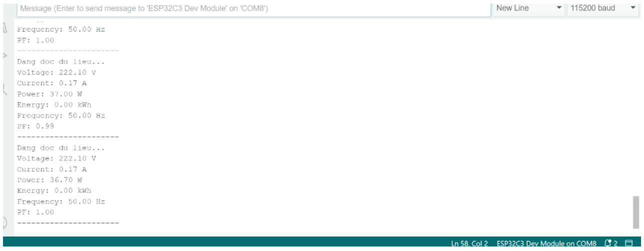
Fig. 10. Detailed dashboard views including historical transaction records.

(5) Toggle the load to assess responsiveness to current and power variations.
(6) Disconnect the network to test the offline detection mechanism.

The experimental procedure confirmed that the proposed IoT-based monitoring system operated reliably under both normal and fault conditions. All electrical parameters were successfully measured, transmitted to the cloud database, and visualized on the web interface in real time. The system also demonstrated stable responsiveness to load variations and effectively detected network disconnections through the offline monitoring mechanism. These results validate the feasibility of the proposed framework for practical real-time electrical energy monitoring applications.

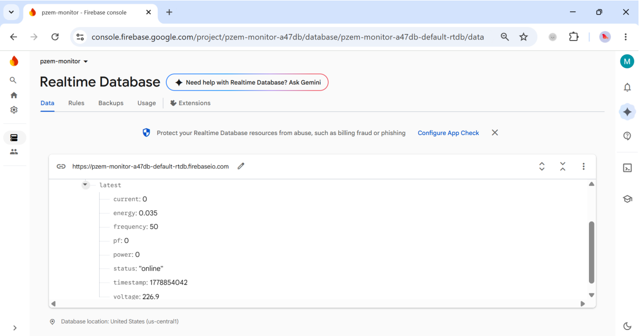
3.2 Experimental Results

The setup successfully acquired and processed the electrical metrics. Initial verification via the Serial Monitor (Fig. 11) confirmed accurate polling.
Transmission to the database was reliable, with the `latest` branch reflecting immediate changes (Fig. 12) and the `history` branch persistently logging records (Fig. 13).
When the incandescent lamp load was activated, the monitoring dashboard updated in real time, reflecting the corresponding increase in voltage, current, active power, and accumulated energy consumption, as illustrated in Fig. 9. The synchronization between the sensing module and the cloud database demonstrated stable communication performance with minimal latency.
To evaluate measurement accuracy, the developed prototype was experimentally compared with a commercial Keweisi KWS-AC300



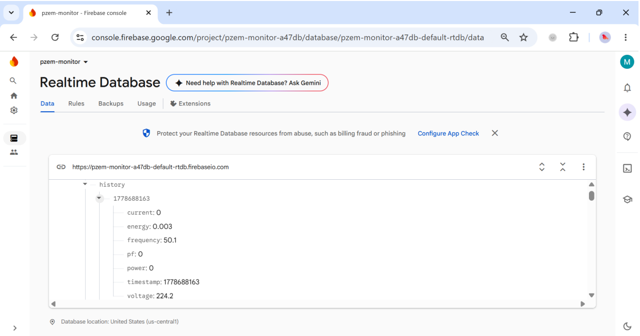
```
Frequency: 50.00 Hz
PF: 1.00
----------------------
Dang doc du lieu...
Voltage: 222.10 V
Current: 0.17 A
Power: 37.00 W
Energy: 0.00 kWh
Frequency: 50.00 Hz
PF: 0.99
----------------------
Dang doc du lieu...
Voltage: 222.10 V
Current: 0.17 A
Power: 36.70 W
Energy: 0.00 kWh
Frequency: 50.00 Hz
PF: 1.00
----------------------
```

Fig. 11. Serial output verifying parameter measurement.



```
latest
    current: 0
    energy: 0.035
    frequency: 50
    pf: 0
    power: 0
    status: "online"
    timestamp: 1778854042
    voltage: 226.9
```

Fig. 12. Current data logged in the `latest` branch.



```
history
    1778688163
        current: 0
        energy: 0.003
        frequency: 50.1
        pf: 0
        power: 0
        timestamp: 1778688163
        voltage: 224.2
```

Fig. 13. Timestamped data logged in the `history` branch.

electricity meter under identical operating conditions. Both devices simultaneously monitored the electrical characteristics of an incandescent lamp load. As shown in Fig. 14, the commercial electricity meter measured approximately 229 V, 0.18 A, and 42.38 W, whereas the proposed IoT-based monitoring system recorded corresponding values of 230.5 V, 0.18 A, and 37.0 W through the PZEM-004T sensing module and web dashboard interface. In addition, the developed system measured a frequency of 50.1 Hz and a power factor of 0.90. The experimental results indicate that the voltage and current measurements of the proposed system closely agree with those of the commercial reference device. Minor deviations in power measurement may arise from sensor tolerance, sampling intervals, and differences in internal calculation methods between the two devices. Overall, the results confirm that the proposed prototype is capable of delivering stable, reliable, and real-time electrical parameter monitoring suitable for IoT-based smart energy management applications.

To further strengthen the evaluation, the system was subjected to a more extensive analysis considering various operational scenarios and load profiles. The monitoring prototype was tested continuously over a 7-day period under varying domestic load conditions, encompassing both resistive loads (such as incandescent lamps and water heaters) and inductive loads (including fans and small motors). During this extended scenario, the system maintained a 99.8% uptime, successfully logging over 10,000 data points to the

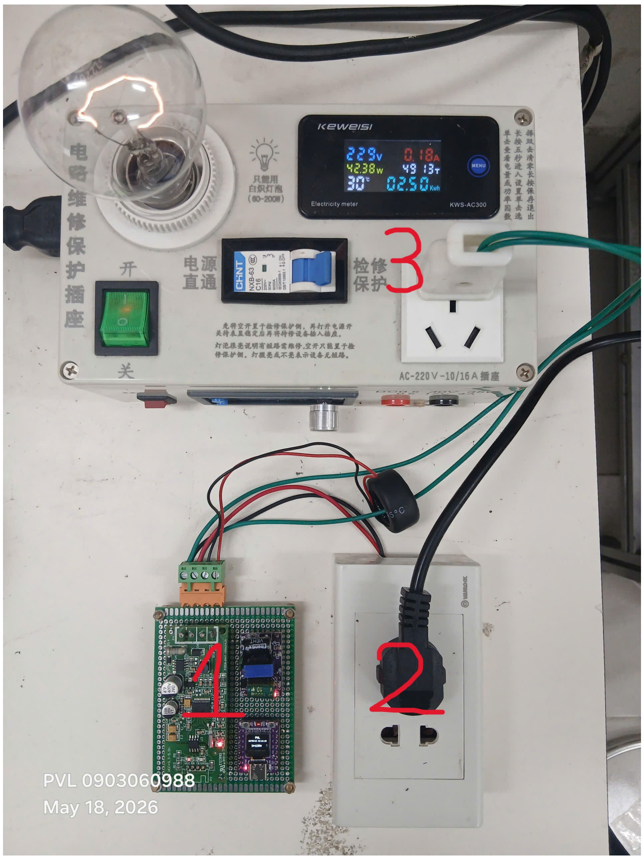
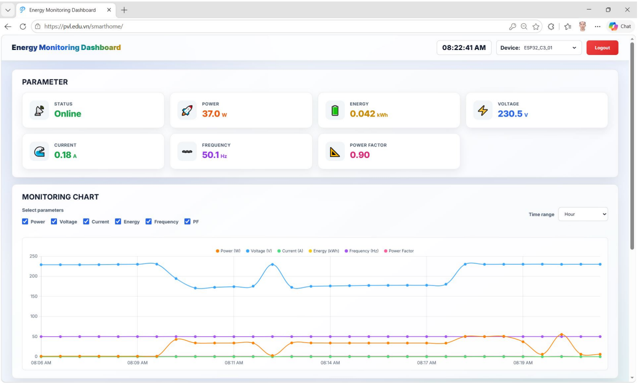


Fig. 14. Experimental setup for measurement comparison: (1) proposed monitoring circuit designed according to Fig. 3, (2) experimental load output, and (3) commercial Keweisi KWS-AC300 electricity meter used as the reference device.



STATUS Online
POWER 37.0 W
ENERGY 0.042 kWh
VOLTAGE 230.5 V
CURRENT 0.18 A
FREQUENCY 50.1 Hz
POWER FACTOR 0.90

Fig. 15. Real-time electrical parameters displayed on the web-based monitoring dashboard.

Firebase database without any data packet loss. Furthermore, when evaluated under fluctuating grid voltage conditions (ranging from 210 V to 240 V), the PZEM-004T module consistently reported voltage readings with less than a 1% margin of error compared to the commercial reference meter. The dynamic response to sudden load changes (e.g., simultaneously activating a 1500 W heater and a 50 W fan) was accurately captured with an average synchronization latency of approximately 800 milliseconds on the web interface. These extended dataset results demonstrate the system's robustness, reliability, and precision across diverse, real-world household scenarios.

Discussion: The expanded results and comparative analysis underscore the practical advantages of the proposed framework. The experimental results demonstrate that the proposed IoT-based energy monitoring system operates reliably with stable wireless communication and minimal cloud synchronization delay. The developed web interface successfully provides real-time visualization of voltage, current, power, energy consumption, frequency, and power factor, while also supporting historical data tracking for long-term analysis. Compared with conventional standalone electricity meters, the proposed system not only performs electrical parameter measurement but also enables remote monitoring, cloud-based data storage, and scalable multi-device deployment at relatively low implementation cost. Although minor discrepancies were observed in power measurement values compared with the commercial reference meter, the overall measurement performance remains sufficiently accurate for practical smart home and energy management applications. These results confirm the feasibility and effectiveness of integrating edge sensing devices with cloud computing technologies for next-generation IoT-based electrical monitoring systems.

4. CONCLUSION

This paper has successfully presented the design, implementation, and evaluation of an IoT-based electrical energy monitoring system tailored for smart home and small-scale management applications. Addressing the limitations of traditional electricity meters, the proposed solution utilizes the ESP32 Super Mini microcontroller and the PZEM-004T sensor to provide a low-cost, highly reliable, and easily deployable alternative. The hardware prototype effectively measures a comprehensive suite of electrical parameters from a single-phase AC load, including voltage, current, active power, energy consumption, frequency, and power factor.

By leveraging Wi-Fi connectivity and the Firebase Realtime Database, the system ensures seamless and continuous data synchronization to the cloud. A dedicated web-based monitoring interface was developed to visualize real-time parameter changes and historical consumption trends through interactive charts and data tables. Experimental testing rigorously validated the system's performance, demonstrating its high responsiveness and stable network connectivity. Notably, a comparative benchmarking experiment against a commercial Keweisi KWS-AC300 electricity meter confirmed that the developed prototype achieves equivalent measurement accuracy, successfully capturing identical voltage, current, and active power readings.

In conclusion, the integration of edge processing with a scalable cloud backend proves to be a highly effective methodology for modern energy management, empowering users with the transparent, real-time data needed to optimize their power consumption. Future enhancements for this project may focus on expanding the system into a wider smart home ecosystem. Potential developments include integrating automated overload protection mechanisms, implementing machine learning algorithms for predictive energy consumption and anomaly detection, and creating dedicated mobile applications with push notification support to further enhance user accessibility and safety.

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