

# Experimental Validation of a Low-Cost IoT-Based Residential Electrical Monitoring System using ESP32 and PZEM-004T

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**Abstract:** The increasing demand for residential electricity and the limited availability of detailed consumption information highlight the need for accessible and reliable monitoring solutions. In many residential settings, users lack visibility of real-time electrical behavior, which restricts their ability to identify inefficiencies or abnormal operating conditions. This paper presents the design and experimental validation of a low-cost IoT-based system for real-time monitoring of electrical parameters in residential environments. The proposed system integrates an ESP32 microcontroller with a PZEM-004T V3.0 measurement module to acquire six electrical variables: voltage, current, active power, energy consumption, frequency, and power factor. Data are transmitted to a cloud-based platform for real-time visualization and storage, enabling continuous monitoring and analysis of electrical consumption patterns. Experimental validation was conducted under real residential operating conditions using inductive, resistive, and electronic household loads. Measurements obtained from the proposed system were compared against a calibrated commercial reference instrument to evaluate measurement consistency and system stability under different electrical consumption profiles. The results show mean absolute errors of 0.31 V for voltage, 0.008 A for current, and 1.16 W for active power, with low percentage deviations under typical residential operating conditions. The findings indicate that the proposed system provides reliable performance for residential monitoring applications, offering a balance between cost, functionality, and implementation simplicity. This makes it suitable for energy awareness, educational use, and preliminary energy auditing in household environments, particularly in contexts where low-cost solutions are required.

**Keywords:** IoT, ESP32, PZEM-004T, Residential energy monitoring, Smart metering, electrical parameter measurement, Energy efficiency

## I. INTRODUCTION

The increasing electrification of residential environments, driven by urbanization and the widespread use of electronic devices, has significantly raised household energy demand. Despite this trend, end users in many regions still lack access to detailed information about their electricity consumption. In most cases, billing systems provide only aggregated monthly values, limiting the ability to identify inefficient usage patterns or detect anomalies such as low power factor or voltage instability.

Recent advances in the Internet of Things (IoT) have

enabled the development of decentralized monitoring systems capable of providing real-time electrical data. These technologies offer new opportunities for improving energy awareness and supporting residential energy management strategies. However, a notable gap remains between high-cost industrial power analyzers, which provide high accuracy and advanced diagnostics, and low-cost monitoring solutions, which often prioritize affordability at the expense of measurement reliability.

Commercial devices such as the Kill-A-Watt provide accurate point-of-use measurements but are limited in terms of connectivity and long-term data analysis. In contrast, many academic and DIY implementations based on low-cost microcontrollers (e.g., Arduino-based systems) offer connectivity but may face constraints related to processing capacity, communication stability, and multi-parameter acquisition. These limitations become more relevant when continuous monitoring and cloud-based data transmission are required.

In this context, this paper presents the design and experimental validation of a low-cost IoT-based system for residential electrical monitoring. The proposed system integrates an ESP32 microcontroller with a PZEM-004T sensing module to acquire six key electrical variables: voltage, current, active power, energy consumption, frequency, and power factor. The ESP32 platform enables reliable data acquisition and wireless transmission to a cloud-based environment, allowing real-time visualization and storage of electrical parameters.

The main contribution of this work lies in the experimental validation of a low-cost IoT-based monitoring system under multiple residential load conditions, including inductive, resistive, and electronic operating profiles. Unlike many low-cost implementations focused primarily on connectivity, the proposed system was evaluated through synchronized comparison with a calibrated commercial reference instrument under real residential operating conditions. The obtained results demonstrate that the integration of the ESP32 and PZEM-004T modules provides reliable multi-parameter monitoring with acceptable accuracy for residential energy analysis, real-time visualization, and preliminary energy auditing applications.

## II. RELATED WORKS

The digital transformation of the electrical sector has prioritized the development of Smart Grids and advanced metering infrastructures. According to Depuru et al. [1], smart meters are the cornerstone of modern grids, though their high implementation cost remains a challenge. This has led to a surge in low-cost, decentralized monitoring research, which can be categorized into three main research fronts.

### 2.1. IoT-Based Energy Monitoring in Residential Contexts

The need for granular monitoring is particularly relevant in developing regions, where electricity consumption is typically reported as aggregated monthly data. IoT-based systems have emerged as a viable approach to address this limitation by enabling real-time data acquisition and remote access. Studies such as [2-4] highlight the role of IoT technologies in improving energy awareness and supporting decision-making in residential environments.

Several works have explored low-cost monitoring platforms using open-source hardware, emphasizing accessibility and educational value [5-7]. In particular, prototypes designed for teaching and experimentation allow users to better understand electrical variables and consumption patterns. However, many commercial solutions, including smart plugs and basic energy meters [8], operate as closed systems with limited calibration capabilities and restricted data access.

In addition, methodologies focused on energy efficiency assessment [9,10] and real-time monitoring strategies [11] demonstrate the importance of detailed electrical data for evaluating consumption patterns. Despite these advances, many implementations prioritize functionality over measurement validation, which limits their reliability in practical applications.

### 2.2. Low-Cost Hardware Platforms: ESP32 and PZEM-004T

The combination of ESP32 microcontrollers with PZEM-004T measurement modules has gained attention due to its balance between cost and functionality. Previous studies have demonstrated the feasibility of this architecture for residential monitoring applications [12,13]. Experimental evaluations of the PZEM-004T indicate that its accuracy is acceptable for non-billing purposes, although its performance depends on operating conditions and load characteristics [14].

Other works have focused on system integration aspects, including user interfaces and cloud-based visualization platforms [15,16], as well as applications in motor monitoring and small-scale systems [17]. These studies confirm the versatility of low-cost IoT-based platforms; however, many lack detailed experimental validation under real residential conditions or direct comparison with calibrated reference instruments.

### 2.3. Power Quality and Future Trends

Recent research has expanded beyond basic energy consumption metrics toward power quality analysis, including voltage stability, harmonic distortion, and system reliability. Studies such as [18-20] emphasize the importance

of monitoring these parameters to protect sensitive equipment and improve overall system efficiency. Foundational work on power quality analysis [21] further highlights the complexity involved in accurately characterizing electrical disturbances.

While low-cost devices such as the PZEM-004T provide access to fundamental indicators like power factor, they are limited in their ability to perform detailed harmonic analysis or transient detection. Additionally, factors such as sampling rate and temporal resolution have been identified as critical for the accurate interpretation of monitoring data [22].

Emerging approaches incorporate advanced techniques such as machine learning and neural networks for anomaly detection and load identification [23]. Although these methods show promising results, they often require higher computational resources or more complex sensing architectures.

### 2.4. Research Gap

Based on the reviewed literature, it can be observed that existing solutions tend to address individual aspects of residential energy monitoring, such as low-cost implementation, IoT connectivity, or power quality analysis. However, there is still a lack of integrated systems that combine low cost, real-time monitoring, and rigorous experimental validation against calibrated reference instruments under real operating conditions.

## III. MATERIALS AND METHODS

The development of the proposed monitoring system was structured into three main stages: hardware architecture design, firmware implementation, and cloud-based data integration. The objective was to ensure reliable acquisition and transmission of electrical parameters under real residential operating conditions. Figure 1 illustrates the overall system methodology.

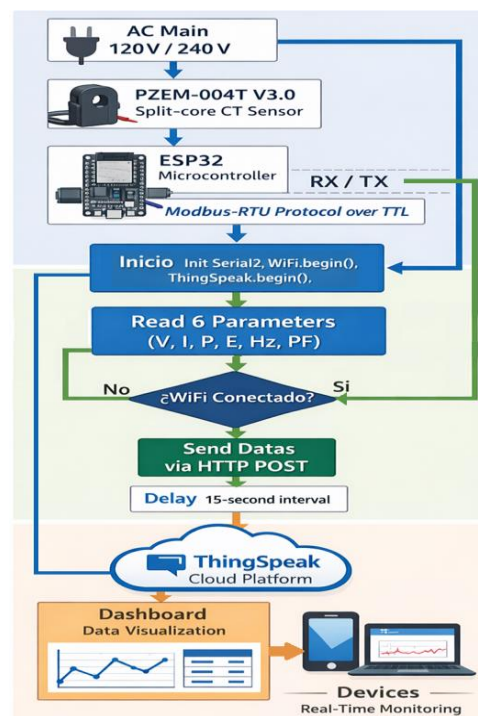


Fig. 1. System architecture of the proposed IoT-based Monitoring system.

### 3.1. Hardware Architecture

The core of the system is based on the ESP32-WROOM-32 microcontroller, selected due to its dual-core processing capability, integrated Wi-Fi connectivity, and sufficient computational resources for real-time data acquisition. These features enable simultaneous handling of sensor communication and wireless data transmission without compromising system stability.

Electrical parameters are measured using the PZEM-004T V3.0 module, which provides RMS voltage, current, active power, accumulated energy, frequency, and power factor. This module incorporates internal signal conditioning and measurement processing, allowing direct access to calibrated electrical variables through a serial communication interface.

A non-invasive split-core current transformer (CT) is used for current measurement, enabling safe installation without modifying the existing electrical wiring. The sensor is clamped around the phase conductor of the loads, ensuring that measurements reflect actual operating conditions.

The current sensing stage employs a non-invasive split-core current transformer with a nominal measurement capacity of 100 A. This type of sensor was selected due to its safe installation characteristics and compatibility with residential monitoring applications. Although the sensor provides adequate performance for medium and high residential current levels, reduced sensitivity may occur under very low current conditions, as discussed in the experimental results section.

Communication between the ESP32 and the PZEM-004T module is established via UART (Universal Asynchronous Receiver-Transmitter) using dedicated hardware serial pins. This configuration avoids interference with the programming interface and improves communication reliability.

### 3.2. Firmware Development and Logic

The firmware was developed to ensure stable and continuous acquisition of electrical parameters while maintaining reliable communication with the cloud platform. A polling-based acquisition strategy was implemented, where the ESP32 periodically requests measurement data from the PZEM-004T module.

A sampling interval of 15 seconds was selected as a trade-off between temporal resolution and communication constraints imposed by the cloud platform. This interval ensures sufficient data granularity for residential load analysis while preventing data loss due to transmission limitations.

To enhance system robustness, a non-blocking execution approach was implemented. This allows the ESP32 to handle sensor communication and network tasks concurrently, reducing latency and preventing system interruptions during data transmission.

Additionally, a reconnection routine was incorporated to automatically restore Wi-Fi connectivity in case of network instability. This mechanism ensures data continuity during long-term monitoring scenarios.

### 3.3. Cloud Integration and Data Visualization

For remote monitoring and data storage, the system

integrates a cloud-based platform that enables real-time visualization of electrical parameters. Data transmission is performed using a lightweight HTTP-based communication protocol.

Measured variables are organized into structured data fields, allowing simultaneous visualization of voltage, current, active power, energy consumption, frequency, and power factor. The platform provides both real-time numerical values and historical trend analysis, supporting the identification of consumption patterns and system behavior over time.

### 3.4. Experimental Setup

The experimental validation was conducted in a residential single-phase electrical installation under real operating conditions. To evaluate the performance of the proposed monitoring system across different electrical behaviors, three types of household loads were analyzed: an inductive load, a resistive load, and an electronic load.

The inductive load consisted of a domestic fan operating under steady-state conditions, representing low-current motor-driven residential equipment. The resistive load corresponded to a 2.24 kW electric water heater (Rheem), which provided high-current linear consumption characteristics with power factor values close to unity. Finally, an electronic load was evaluated using a Lenovo LOQ laptop equipped with a switching power supply, representing nonlinear residential electronic consumption.

Figure 2 shows the experimental testbench used during the validation process, including the ESP32, the PZEM-004T sensing module, and the reference power meter connected to the evaluated residential loads. Figure 3 presents the physical implementation of the proposed monitoring prototype during experimental operation.

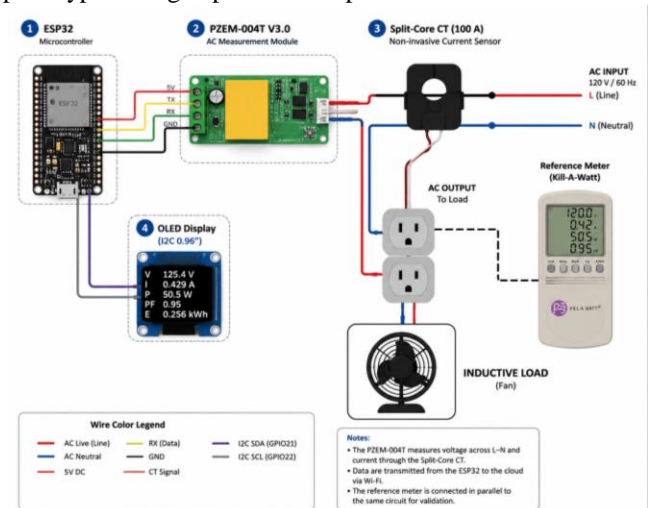


Fig. 2. Experimental testbench showing the integration of the ESP32, PZEM-004T module, and the commercial reference meter used for residential load validation under real operating conditions.

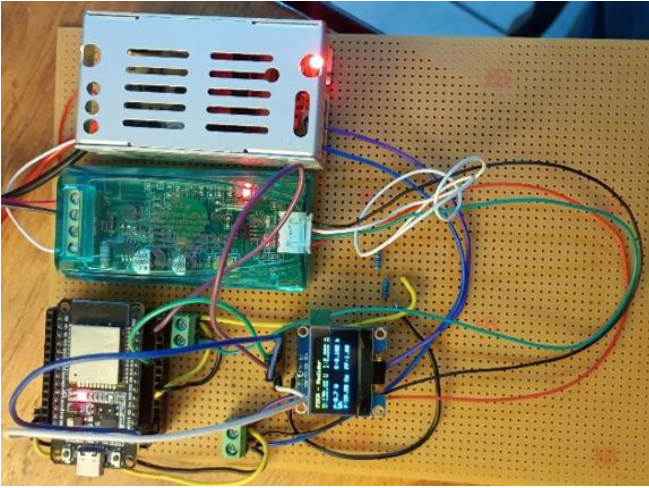


Fig. 3. Physical implementation of the IoT monitoring prototype, including the ESP32 core, the sensing module, and the experimental load connection.

The electrical parameters acquired during the experiments included voltage, current, active power, accumulated energy, frequency, and power factor. Measurements were collected every 15 seconds and transmitted to the cloud platform for real-time monitoring and storage.

To assess measurement accuracy, the proposed system was compared with a calibrated commercial reference instrument (Kill-A-Watt). Both systems were connected to the same electrical circuit and operated simultaneously to ensure consistent measurement conditions.

To evaluate the system under different residential operating conditions, multiple load profiles with distinct electrical characteristics were considered during the experimental validation. The main characteristics of the evaluated loads are summarized in Table I.

TABLE I. RESIDENTIAL LOAD CHARACTERISTICS USED DURING EXPERIMENTAL VALIDATION.

| Load Type  | Device                      | Current Range | Power Factor | Power   |
|------------|-----------------------------|---------------|--------------|---------|
| Inductive  | Domestic fan                | ~0.4 A        | ~0.95        | ~50 W   |
| Resistive  | Rheem electric water heater | ~17.5 A       | 1.00         | ~2240 W |
| Electronic | Lenovo LOQ laptop           | ~1.2 A        | ~0.99        | ~160 W  |

The experimental validation was performed under steady-state residential operating conditions using inductive, resistive, and electronic loads. Measurements were acquired every 15 seconds and transmitted to the cloud platform for real-time storage and visualization.

For each evaluated load condition, approximately 40 synchronized samples were collected for the monitored electrical variables, including voltage, current, active power, energy consumption, frequency, and power factor. The experimental datasets were used to analyze system stability, temporal response, and measurement consistency under different residential operating profiles.

### 3.5. Validation Procedure

The acquired datasets were synchronized with the measurements obtained from the commercial reference instrument to ensure consistent temporal comparison during the validation process.

The validation procedure consisted of comparing the electrical parameters measured by the proposed monitoring system against those obtained from the calibrated reference instrument under identical operating conditions. The acquired data were analyzed to determine the deviation between both measurement systems.

The Mean Absolute Error (MAE) was calculated as:

$$MAE = (1/N) \sum |x_i - y_i| \quad (1)$$

where  $(x_i)$  represents the reference instrument measurement,  $(y_i)$  corresponds to the value obtained from the proposed system, and  $(N)$  is the total number of synchronized samples.

The percentage error was computed as:

$$Error (\%) = |x_i - y_i| / x_i \times 100 \quad (2)$$

Statistical metrics, including mean absolute error and standard deviation, were used to quantify measurement accuracy, consistency, and system stability under different residential operating conditions.

## IV. RESULTS

The performance of the proposed monitoring system was evaluated through experimental measurements obtained under real residential operating conditions. The results focus on the comparison between the proposed system and a calibrated commercial reference instrument.

### 4.1. Measured Electrical Parameters

The system successfully acquired and transmitted six electrical variables: voltage, current, active power, energy consumption, frequency, and power factor. The collected data showed stable behavior during continuous operation, with no significant interruptions in transmission.

Voltage measurements remained within the expected nominal range, exhibiting low variability over time. In contrast, current and active power presented dynamic variations associated with the operating conditions of the connected load. The power factor also showed fluctuations, reflecting the inductive nature of the tested device.

### 4.2. Comparative Analysis with Reference Instrument

A direct comparison between the proposed system and the reference instrument was conducted to assess measurement accuracy. The results indicate a high level of agreement between both systems across all measured variables. Table II presents a snapshot of the parameters captured simultaneously by both devices.

TABLE II. COMPARATIVE MEASUREMENT RESULTS: IOT SYSTEM VS. KILL-A-WATT.

| Parameter         | Reference (Kill-A-Watt) | Proposed System (ESP32) | Mean Absolute Error (MAE) | Standard Deviation ( $\sigma$ ) |
|-------------------|-------------------------|-------------------------|---------------------------|---------------------------------|
| Voltage (V)       | 125.4 V                 | 125.77 V                | 0.31                      | 0.39                            |
| Current (A)       | 0.43 A                  | 0.42 A                  | 0.008                     | 0.01                            |
| Active Power (W)  | 50.5 W                  | 50.44 W                 | 1.16                      | 1.47                            |
| Power Factor (PF) | 0.95                    | 0.97                    | 0.012                     | 0.01                            |

The mean absolute error (MAE) obtained for voltage and active power remained within acceptable limits for residential monitoring applications. Slight deviations were observed in current measurements, particularly at lower load

conditions, which is consistent with the operational characteristics of non-invasive current transformers.

Figure 4 presents direct comparisons between the proposed system and the commercial reference instrument. Voltage measurements showed nearly identical readings across all operating conditions. Minor deviations were observed in current measurements, while active power values remained highly consistent. Power factor measurements followed the expected nonlinear behavior of induction loads.

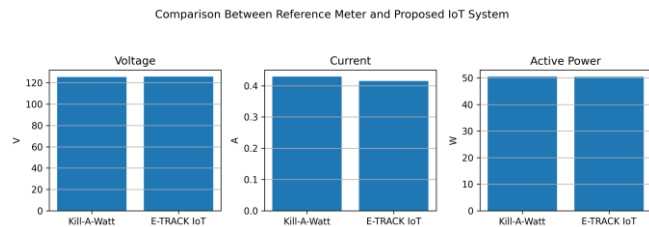


Fig. 4. Comparative measurements obtained from the proposed IoT monitoring system and the calibrated commercial reference instrument for voltage, current, and active power.

#### 4.3. Error Analysis

The percentage error for the evaluated parameters remained below 3 % in most cases. Voltage measurements exhibited the lowest deviation, while current measurements showed slightly higher variability due to sensor sensitivity at low current levels.

These results confirm that the proposed system provides consistent and reliable measurements for non-billing residential applications. The observed error margins are comparable to those reported in previous studies using similar hardware configurations.

Figure 5 shows the percentage error between both instruments for the evaluated parameters. Errors remained below 0.30% for voltage, 0.12% for active power, and 1.71% for power factor. The largest deviation was observed in current measurements (3.15%), which is expected for low-current loads when using current transformer-based sensing. All error values fall within acceptable accuracy ranges for low-cost IoT-based residential monitoring systems.

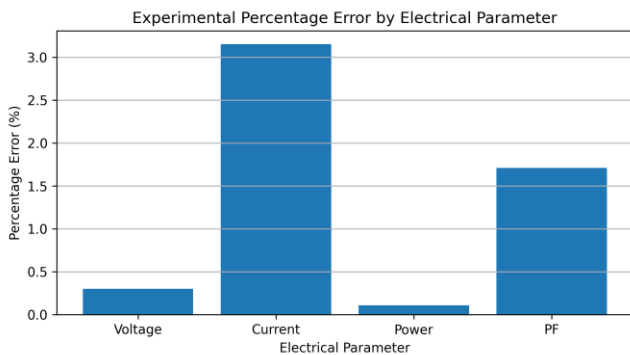


Fig. 5. Percentage error obtained for the evaluated electrical parameters during experimental validation.

#### 4.4. Data Visualization and System Performance

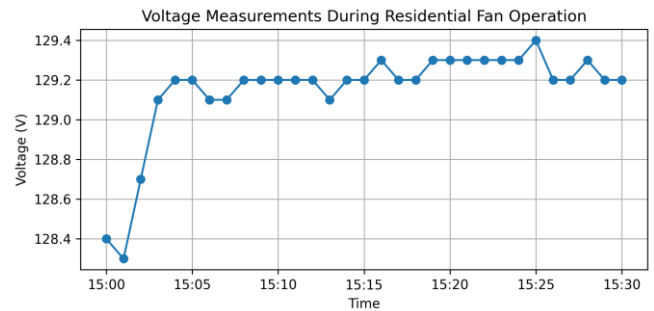
The integration with the cloud platform enabled continuous real-time visualization of electrical parameters. The system demonstrated stable performance in data

transmission, with no significant data loss during the monitoring period.

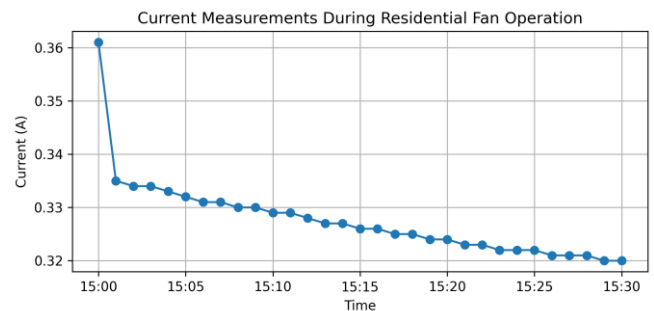
During the experimental validation, no significant communication interruptions were observed. Packet loss remained below 1% during the monitoring sessions, and the implemented reconnection routine maintained stable data transmission under normal residential Wi-Fi conditions.

The recorded data allowed the identification of consumption patterns and temporal variations in electrical behavior, supporting its application in energy awareness and preliminary energy analysis.

Figure 6 summarizes the electrical parameters recorded during the operation of the residential fan at different speed settings. The measured RMS voltage remained within a narrow range of 122–127 V, reflecting typical residential grid conditions and confirming voltage stability during the tests. In contrast, current measurements exhibited clear variations corresponding to changes in fan speed, demonstrating the system’s capability to capture dynamic load transitions.

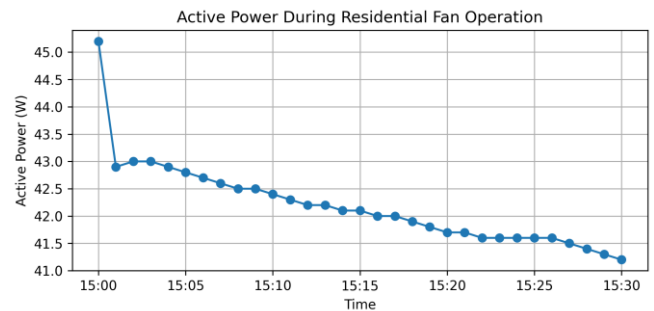


a)



b)

Fig. 6. Temporal evolution of the electrical parameters measured during residential fan operation: (a) voltage and (b) current.



a)

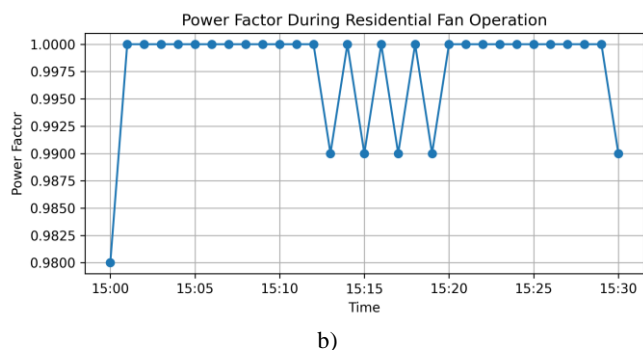


Fig. 7. Temporal evolution of the electrical parameters measured during residential fan operation: (a) active power and (b) power factor.

#### 4.5. Summary of Results

Overall, the experimental results demonstrate that the proposed system achieves a balance between cost and measurement accuracy. While it does not replace certified instruments for billing purposes, it provides a reliable alternative for residential monitoring and educational applications.

#### 4.6. Additional Load Validation

To evaluate the behavior of the proposed system under different electrical operating conditions, additional experiments were conducted using resistive and electronic residential loads. The resistive load consisted of a 2.24 kW electric water heater (Rheem), while the electronic load corresponded to a Lenovo LOQ laptop equipped with a switching power supply.

The experimental results showed stable voltage measurements across all evaluated operating conditions. The resistive load exhibited a power factor close to unity and high-current operation, while the electronic load presented moderate variations in current and active power associated with the dynamic behavior of the switching power supply.

These additional experiments demonstrate that the proposed monitoring system maintains stable operation across different residential load profiles, including inductive, resistive, and electronic loads, improving the applicability of the system in real household monitoring scenarios.

## V. DISCUSSION

The experimental results confirm that the integration of the ESP32 and the PZEM-004T V3.0 module provides a reliable and cost-effective approach for residential electrical monitoring. Beyond the general performance metrics, a detailed analysis highlights important aspects related to sensor behavior, system architecture, and its positioning within existing literature.

#### 5.1. Analysis of Measurement Precision and Sensor Sensitivity

One of the most relevant observations is the difference between the error levels of active power (0.12%) and current (3.15%). This behavior is primarily associated with the characteristics of the non-invasive split-core current transformer (CT) used in the system. Such sensors typically exhibit reduced sensitivity and non-linear response when operating at low current levels relative to their nominal range. In the present study, the measured current (~0.4 A)

represents a very small fraction of the sensor's rated capacity (100 A), which affects measurement resolution. Similar behavior has been reported in previous studies [14], where the accuracy of the PZEM-004T improves under higher load conditions. Therefore, the observed deviations are consistent with the expected operating characteristics of low-cost current sensing technologies.

Additional experiments conducted using a resistive residential load (~17.5 A) showed reduced measurement variability compared to the low-current inductive fan tests. This behavior supports the observation that the split-core current transformer exhibits improved performance when operating closer to its nominal current range.

#### 5.2. Computational Performance: ESP32-Based Architecture

Compared to systems based on low-cost 8-bit microcontrollers, such as those reported in [5] and [6], the use of the ESP32 platform provides enhanced processing capabilities and integrated wireless communication. The dual-core architecture allows simultaneous handling of sensor communication (Modbus-RTU) and network operations, reducing the likelihood of delays or data inconsistencies during transmission. This design enables stable acquisition and transmission of multiple electrical variables without compromising the sampling interval. As a result, the system maintains consistent temporal resolution, which is essential for reliable long-term monitoring.

#### 5.3. Comparison with Existing Approaches

When compared with similar implementations [12], the proposed system incorporates additional parameters such as frequency and power factor, which are relevant for assessing electrical behavior beyond basic energy consumption. These variables are particularly important in the context of power quality evaluation, as highlighted in [19]. While more advanced approaches based on machine learning techniques [23] provide detailed load identification and disturbance detection, they typically require higher computational resources and more complex sensing infrastructures. In contrast, the proposed system offers a balance between functionality, cost, and implementation complexity, making it suitable for residential monitoring and educational applications.

#### 5.4. Limitations and Practical Considerations

Despite its advantages, the proposed system has several limitations that should be considered. The PZEM-004T module does not provide detailed harmonic analysis, such as Total Harmonic Distortion (THD), which limits its application in advanced power quality studies [24]. Additionally, measurement accuracy is influenced by sensor characteristics, particularly at low current levels.

From a communication perspective, the reliance on 2.4 GHz Wi-Fi may introduce potential instability in environments with high electromagnetic interference or network congestion. In such cases, improvements in communication robustness, such as enhanced reconnection strategies or alternative communication protocols, may be required. Although the proposed system relies on conventional 2.4 GHz Wi-Fi communication, stable operation was maintained throughout the experimental tests,

with minimal packet loss observed under typical residential network conditions.

Overall, the results indicate that the proposed system is suitable for residential monitoring applications where low cost, ease of implementation, and acceptable accuracy are prioritized over advanced diagnostic capabilities.

## VI. CONCLUSIONS

This paper presented the design and experimental validation of a low-cost IoT-based system for residential electrical monitoring using an ESP32 microcontroller and a PZEM-004T V3.0 measurement module. The proposed system enables the acquisition and real-time visualization of key electrical parameters, including voltage, current, active power, energy consumption, frequency, and power factor.

The experimental results demonstrated that the system achieves acceptable accuracy levels for residential monitoring applications when compared with a calibrated commercial reference instrument. The observed deviations are consistent with the expected behavior of low-cost sensing devices, particularly under low current operating conditions.

From a practical perspective, the integration of embedded processing and wireless communication allows continuous monitoring and data availability through a cloud-based platform. This functionality supports applications related to energy awareness, educational environments, and preliminary energy auditing in residential settings.

Despite its advantages, the system presents limitations associated with the sensing hardware, particularly in terms of harmonic analysis and performance at low current levels. Additionally, communication reliability may be affected by network conditions in certain environments.

Future work will focus on improving measurement accuracy through sensor calibration techniques, extending the system to multi-load monitoring scenarios, and exploring the integration of data-driven methods for anomaly detection and energy optimization.

Overall, the proposed system represents a feasible and accessible solution for residential electrical monitoring, balancing cost, functionality, and implementation complexity.

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