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IoT Based Electrical Energy Consumption Monitoring System Design

Rancang Bangun Sistem *Monitoring* Konsumsi Energi Listrik Berbasis *Internet of Things* (IoT)

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Abstract

Conventional kWh meters have a functional limitation: they measure household electrical energy consumption without the ability to control electrical loads, which can lead to uncontrolled energy use and high electricity costs. This study aims to design and build an Internet of Things (IoT)-based energy monitoring system capable of tracking electrical parameters in real time while automatically and remotely controlling electrical loads. The novelty of this research lies in the variation of testing time, the type and capacity of loads used, and the evaluation of the system's energy-saving effectiveness under energy-limiting control. The system was evaluated using an error percentage calculation method, with a Taffware KWE-PM01 wattmeter as the comparison standard, the 5V Songle relay datasheet, and efficiency savings calculations. Results show that the PZEM-004T sensor's measurement error percentage remained below the ±5% tolerance limit, with a maximum error of 4.3%. Relay response time ranged from 0.2 to 1.3 seconds, and the system improved electrical energy efficiency by 31.01% for LED lamp loads and 30.83% for electric fan loads by setting a daily energy consumption limit for each load. Overall, the designed system proved reliable in terms of measurement accuracy, relay response time, and energy-saving efficiency.

Keywords: IoT, ESP32, PZEM—004T, Blynk, electrical energy monitoring, energy saving

Abstrak

Penggunaan kWh meter konvensional dalam memantau konsumsi energi listrik rumah tangga memiliki keterbatasan fungsi yaitu mengukur energi tanpa disertai kemampuan pengontrolan beban listrik, hal ini dapat menyebabkan konsumsi energi listrik tidak terkontrol dan mengakibatkan tingginya biaya penggunaan listrik. Penelitian ini bertujuan untuk merancang dan membangun sistem monitoring konsumsi energi listrik berbasis Internet of Things (IoT), yang mampu memantau parameter listrik secara real-time serta mengendalikan beban listrik secara otomatis dan jarak jauh. Kebaruan penelitian ini terletak pada variasi waktu pengujian, jenis dan kapasitas beban, serta evaluasi efektivitas penghematan energi sistem di bawah kontrol pembatasan energi. Sistem ini dievaluasi menggunakan metode perhitungan persentase error *dengan alat standar pembanding wattmeter Taffware KWE-PM01,* datasheet relay *Songle 5V, dan perhitungan penghematan efisiensi. Hasil pengujian menunjukkan nilai persentase* error *pengukuran sensor PZEM-004T berada di bawah batas toleransi ±5% dengan* error *maksimum sebesar 4,3%, waktu respon* relay *berkisar antara 0,2 hingga 1,3 detik, dan sistem mampu meningkatkan efisiensi penggunaan energi listrik sebesar 31,01% pada beban lampu LED dan 30,83% pada beban kipas angin melalui pemberian batas energi listrik yang dikonsumsi oleh masing-masing beban di setiap harinya. Dengan demikian, sistem yang dirancang dapat dikatakan andal dalam akurasi pengukuran, waktu respon* relay*, dan efisiensi penghematan energi listrik.*

Kata Kunci: IoT, ESP32, PZEM-004T, Blynk, monitoring energi listrik, penghematan energi

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1 Introduction

Electricity has become a basic necessity in daily life, with national per capita electricity consumption continuously increasing from 2019 to 2024 [1]. As consumption rises, efficient electricity utilization is essential to avoid waste; uncontrolled electricity usage can lead to excessive energy consumption, higher costs, and increased energy burden [2],[3],[4] . Internet of Things (IoT) technology offers a promising solution by enabling remote monitoring and control of electricity consumption without requiring direct physical presence at the device location [5]. This aligns with Indonesia's broader digital transformation agenda under the Making Indonesia 4.0 roadmap [6], as well as national efforts to expand IoT adoption across various sectors, although infrastructure limitations and human resource constraints remain challenges to its optimal utilization [7]. In support of national energy efficiency goals, the Indonesian government issued Government Regulation No. 33 of 2023 concerning Energy Conservation [8].

Electrical energy consumption refers to electricity usage in the household, industrial, commercial, and transportation sectors, which is commonly measured using a kWh meter. While conventional kWh meters provide reasonably effective measurement, they lack load-control capability, often resulting in fluctuating energy consumption and high electricity costs [9]. Therefore, achieving efficient electricity usage requires load control, which can be realized through an IoT-based system [10],[11],[12]. Such a system generally connects electronic devices via the internet, with a microcontroller processing data from voltage and current sensors and transmitting it via Wi-Fi to a monitoring platform in real time, while a relay regulated by the microcontroller performs load control [13],[14],[15]. The ESP32 microcontroller combined with the Blynk application is widely used for monitoring and control purposes due to its proven effectiveness [16],[17],[18]. Referring to Muksin and Tjahjono [16], the developed IoT-based monitoring and control system was able to improve power control efficiency by up to 70%.

This study aims to design and build an IoT-based electrical energy consumption monitoring system capable of monitoring electrical parameters (voltage, current, power, energy, frequency, and power factor) in real time while automatically and remotely controlling electrical loads. Previous research by Muhammad and Sardi [19] developed an IoT-based household electrical power monitoring system using the PZEM-004T sensor. Their evaluation involved several household loads with different power capacities, including a 45 W fan, a 65 W laptop charger, and 350 W appliances such as an iron and a rice cooker. The energy consumption of these loads was monitored at different durations, ranging from 15 to 120 minutes [19]. However, their study primarily focused on monitoring household electrical power consumption, while the reliability of an integrated load-control mechanism for limiting electrical energy consumption over an extended period was not comprehensively evaluated. The present study evaluates the PZEM-004T measurement performance under different time conditions using low-, medium-, and high-capacity loads. In addition, the developed system integrates automatic and remote load control based on energy and power limits, as well as reliability testing over an extended period to evaluate its effectiveness in restricting electrical energy consumption. Therefore, the contribution of this study is the integration of varied testing conditions with an IoT-based load-control mechanism and extended reliability evaluation for limiting electrical energy consumption.

The system employs an ESP32 microcontroller and a PZEM-004T sensor for measurement, equipped with a relay to cut off the electricity supply once the consumption limit is reached, with the Blynk application used for remote monitoring and control. Testing was conducted by measuring electrical parameters under loaded and unloaded conditions using the designed system and standard measurement instruments, as well as evaluating electricity usage before and after implementing the system. The results of this study are expected to improve electricity usage efficiency, reduce energy waste, and enable users to manage their energy consumption more wisely through IoT-based technology.

2 Method

2.1 Method Used

The research methodology used in this study is quantitative data collection. The research began with a system design stage using two PZEM-004T 100A v4 sensors to measure electrical parameters, including voltage, current, power, energy, frequency, and power factor, with the resulting data processed by an ESP32 WROOM microcontroller. This microcontroller functions to process measurement data, control a relay as a load switch, and transmit data to the Blynk application via a local server as well as to Google Spreadsheets via a Wi-Fi network in real time. During the hardware development stage, components such as the sensors, microcontroller, relay, OLED display, and keypad were designed and assembled into a single panel for implementation in a household with a 900 VA power connection. The monitoring data is displayed on the OLED screen for local monitoring purposes, as well as on the Blynk application for remote monitoring. Testing was carried out to ensure system reliability, starting with sensor accuracy testing by comparing the sensor measurement results with a standard measuring instrument, the Taffware KWE-PM01 wattmeter, followed by relay response time testing, and finally testing the system's reliability in limiting electrical energy consumption.

2.2 Tools and Materials

2.2.1 Tools

The tools used in this research include both hardware and software. The complete details of the hardware are shown in Table 1.

Table 1. Hardware

No	Tools	Specification	Quantity	Description
1	Laptop	ASUS X441MA, Intel(R) Celeron(R) N4000 CPU 1.10 GHz, RAM 4 GB, 500 GB HDD	1	Used for support the design and construction process of devices and data processing.
2	Handphone	Samsung A6 Exynos 7870, RAM 3 GB, ROM 32 GB	1	Used for remote monitoring and control via the Blynk application.
3	Wattmeter	Tafware KWE-PM01	1	Used for comparison with the designed device.

The complete details of the software used are shown in Table 2.

Table 2. Software

No	Platform	Specification	Description
1	Arduino IDE	2.3.4	Used for write programs for the device.
2	Blynk	2.27.34	Used for monitor and control the system.
3	Google Spreadsheet	JavaScript (V8 Engine)	Used for storage of historical measurement data of the device.

2.2.2 Materials

The materials used in the construction of the device are shown in Table 3.

Table 3. Hardware Materials

No.	Material	Quantity	Description
1	ESP32 WROOM	1	Used for data processing and system control.
2	0.96-inch White I2C OLED Display	1	Used for display measurement results.
3	PZEM-004T 100A Sensor	2	Used for measure electrical parameters.
4	5 V DC Relay	2	Used for disconnect or connect the power supply to the load.
5	4 x 4 Keypad	1	Used for manual control and device configuration.
6	PCF8574 I2C	1	Used for add I/O pins to the ESP32.
7	LM2596	1	Used for step down the voltage from 12 V to 5 V.
8	12 V DC Adapter	1	Used for supply power to the LM2596 module.
9	2-Hole Electrical Outlet	1	Used to install household electrical equipment.
10	STB TX3 Mini	1	Used for local Blynk servers.
11	MikroTik hAP ac lite	1	Used for network access management and configuration.

3 System Design

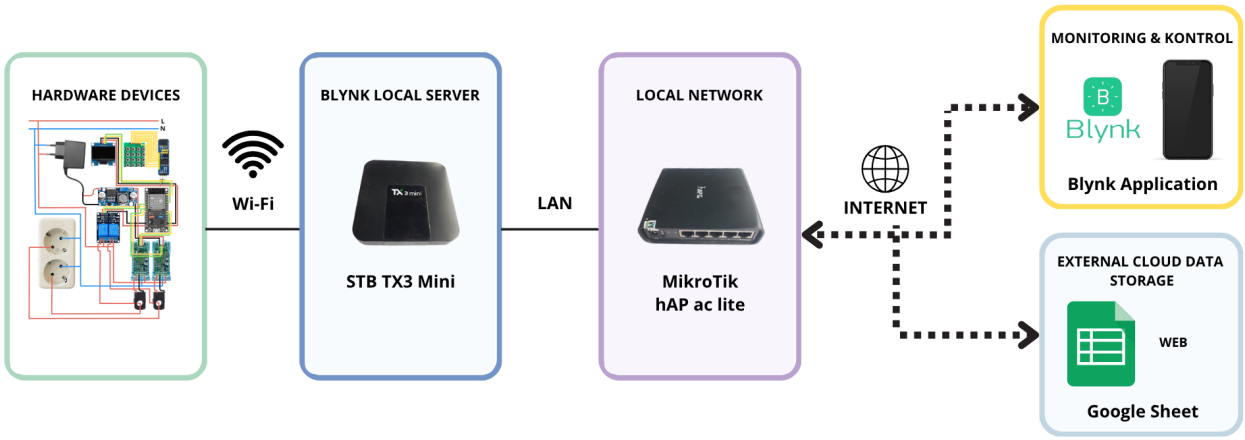


Figure 1. Block diagram of the hybrid-based IoT system

Figure 1 shows the overall system, which consists of hardware, a local Blynk server, a MikroTik router, as well as the Blynk application and Google Spreadsheet connected via an internet network. The system is designed with two clouds, namely internal and external. The internal cloud is the STB TX3 Mini, which functions as a local server for storing data used by the Blynk application, while the external cloud is Google Spreadsheet, which serves as an outside server for storing the electrical load measurement data.

3.1 Working Principle of the Device

The designed system operates on the principle of monitoring and controlling electrical load usage. The system begins electrical monitoring once the relay has been activated by the user. Users can monitor the electrical usage of the load through the Blynk application or the OLED display and control the currently active load through the Blynk application or the keypad. Load control includes ON/OFF control, setting an energy usage limit for the load, setting a power usage limit for the load, setting an on-duration, and setting an automatic ON/OFF schedule.

The energy usage limit is a control feature that allows users to specify the maximum amount of electrical energy that can be consumed by the load. The system continuously monitors the accumulated energy consumption measured by the PZEM-004T sensor and compares it with the energy limit specified by the user. When the accumulated energy consumption reaches the specified limit, the relay automatically disconnects the electrical supply to the load. This feature is intended to prevent the load from consuming electrical energy beyond the user's specified limit. In this study, the energy limit control feature was also evaluated as part of the system reliability testing using an LED lamp and a fan over a two-week testing period.

Users can select the desired control feature to help limit the electrical energy consumption of the load. The relay will cut off the electrical supply to the load when one of the activated control features reaches the limit set by the user. The complete details of the device's workflow are shown in Figure 2.

3.2 Wiring Diagram

The wiring diagram of the designed device is shown in Figure 3.

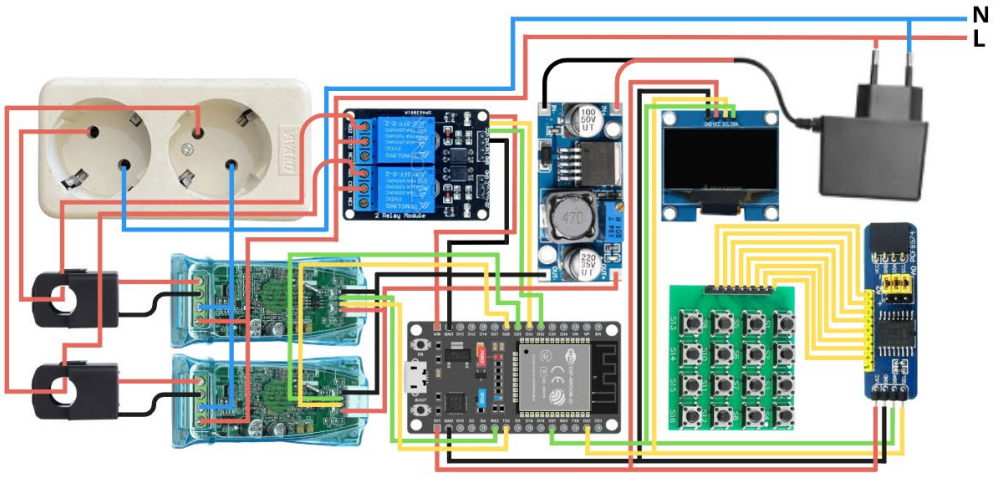


Figure 3. Wiring diagram of the designed device

3.3 Hardware Construction of the Device

The design of the IoT-based electrical energy consumption monitoring device is shown in Figure 4.

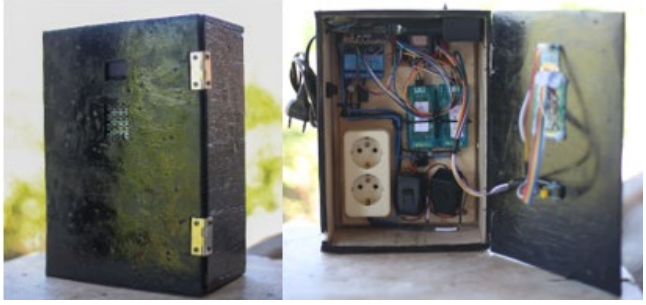


Figure 4. Hardware construction of the device

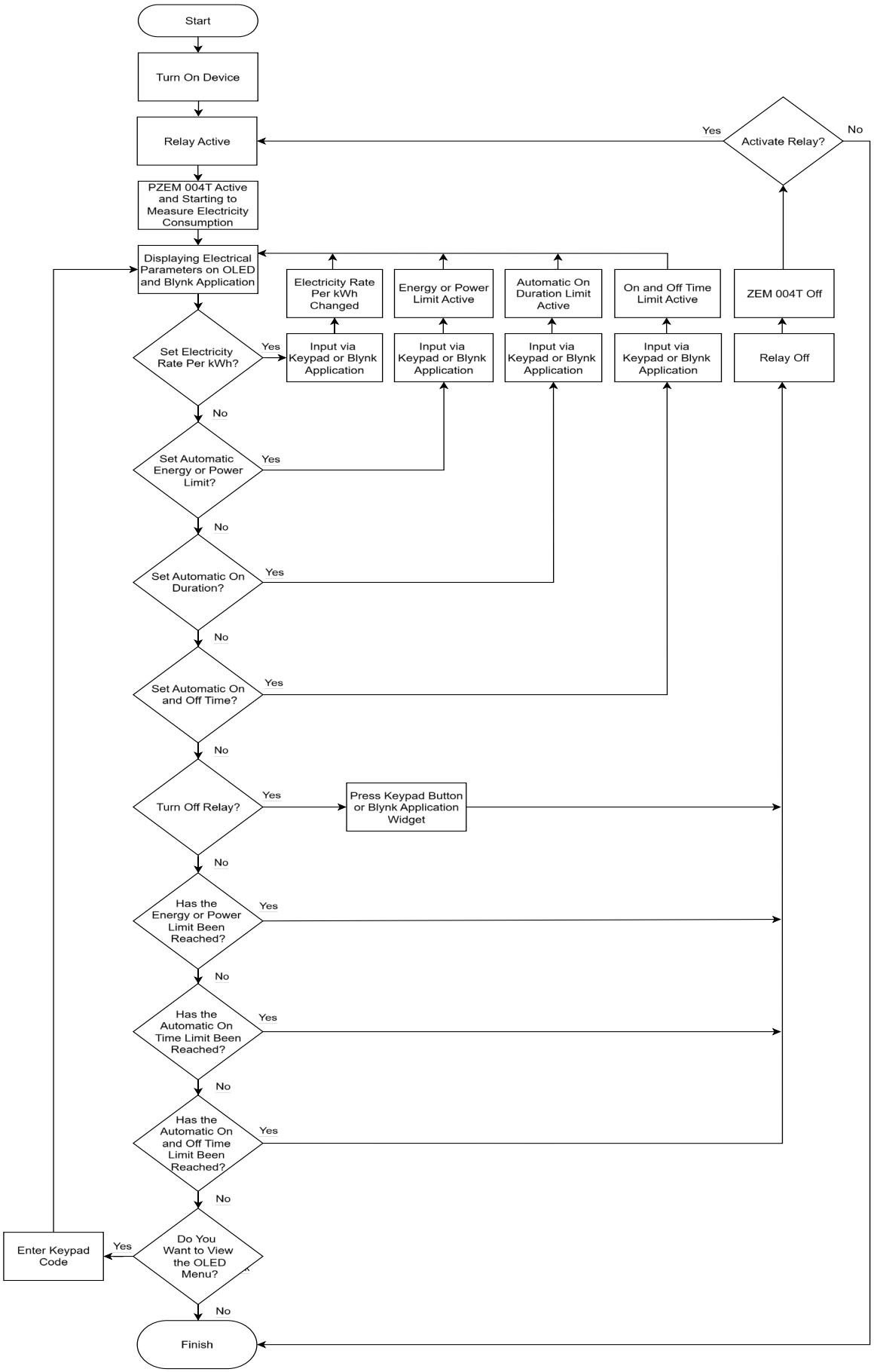


Figure 2. Working principle of the device

3.4 Dashboard for Monitoring and Controlling Electricity Usage

The Blynk application dashboard for monitoring and controlling electricity consumption is shown in Figure 5.

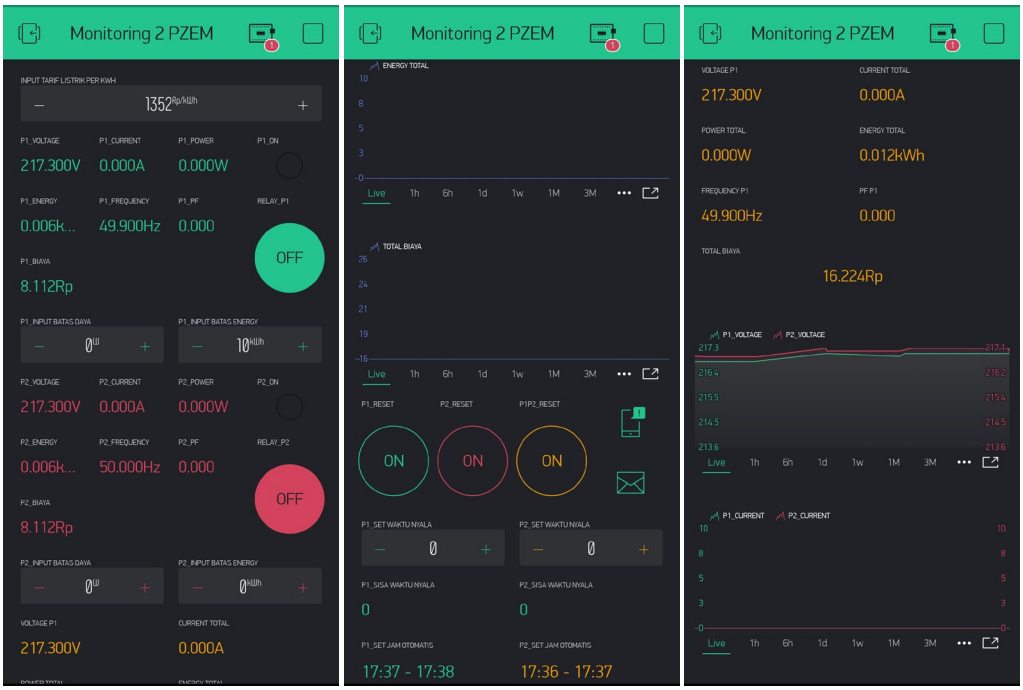


Figure 5. Monitoring and control dashboard on the Blynk application

4 Results and Discussion

4.1 Accuracy Testing of the PZEM-004T Sensor

The accuracy testing of the PZEM-004T sensor aims to determine the accuracy level of the PZEM-004T sensor in measuring electrical parameters through the application of variations in time, load type, and load capacity used. This testing was carried out using two different types of tests: testing with time variation without load, and testing with time variation with load. The time variations include 06:00-06:58, 09:00-09:58, 13:00-13:58, and 20:00-20:58. The types and capacities of loads used include a laptop charger (low), a rice cooker (medium), and a motor (high).

4.1.1 Accuracy Testing of the PZEM-004T Sensor Based on Time Variation without Load

Table 4. Voltage measurement results of PZEM-004T vs wattmeter under no-load condition

Time	PZEM (V)	Wattmeter (V)	%Error
06:00-06:58	213.62 ± 3.94	212.65 ± 3.86	0.4561
09:00-09:58	211.98 ± 2.99	211.07 ± 3.01	0.4311
13:00-13:58	203.02 ± 2.51	202.14 ± 2.51	0.4353
20:00-20:58	202.63 ± 2.68	201.67 ± 2.66	0.4760

Note: Values are presented as mean ± standard deviation (SD) based on 30 measurements recorded at 2-minute intervals.

Table 4 summarizes the sensor's voltage readings under no-load conditions across the four testing windows. Across all periods, the PZEM-004T tracked the wattmeter closely: its mean voltage spanned 202.63-213.62 V against 201.67-212.65 V for the wattmeter, with comparable variability (SD 2.51-3.94 V versus 2.51-3.86 V). Percentage error stayed confined to a narrow 0.4311%-0.4760% band, well under the 5% threshold typically taken as evidence of properly functioning measurement hardware suitable for real-time monitoring [20]. Such tight, consistent agreement across every time window confirms that the PZEM-004T's voltage sensing remains reliable even in the absence of a load.

4.1.2 Accuracy Testing of the PZEM-004T Sensor Based on Time Variation with Load

Table 5. Current measurement results of PZEM-004T vs wattmeter under load condition

Time	Laptop charger			Magic Com			Motor		
	PZEM (A)	Wattmeter (A)	%Error	PZEM (A)	Wattmeter (A)	%Error	PZEM (A)	Wattmeter (A)	%Error
06:00-06:58	0.1114 ± 0.00246	0.1090 ± 0.00000	2.2018	0.3078 ± 0.00140	0.3070 ± 0.00000	0.2606	1.1292 ± 0.03421	1.1499 ± 0.03896	1.8002
09:00-09:58	0.1090 ± 0.01287	0.1090 ± 0.01372	0.0000	0.2840 ± 0.00516	0.2839 ± 0.00348	0.0352	0.8400 ± 0.01944	0.8484 ± 0.02802	0.9901
13:00-13:58	0.0690 ± 0.01969	0.0705 ± 0.01739	2.1277	0.2860 ± 0.00516	0.2905 ± 0.00580	1.5491	0.8210 ± 0.03143	0.8528 ± 0.02734	3.7289
20:00-20:58	0.1100 ± 0.00000	0.1090 ± 0.00000	0.9174	0.3100 ± 0.00000	0.3170 ± 0.00000	2.2082	1.1080 ± 0.02098	1.1378 ± 0.01855	2.6191

Notes: Values are presented as mean ± standard deviation (SD) based on 10 measurements recorded at 2-minute intervals.

Current measurements under load are summarized in Table 5, covering three representative loads-a laptop charger (low), a rice cooker (medium), and a motor (high)-tested across the same four time windows. The PZEM-004T's readings tracked the wattmeter closely for every load: 0.069-0.111 A versus 0.071-0.109 A for the charger, 0.284-0.310 A versus 0.284-0.317 A for the rice cooker, and 0.821-1.129 A versus 0.848-1.150 A for the motor. Percentage errors stayed within 06-2.20% for the charger, 0.04%-2.21% for the rice cooker, and 0.99%-3.73% for the motor, all comfortably inside the 5% tolerance limit. These results point to dependable current-sensing performance across a wide load range.

Table 6. Power measurement results of PZEM-004T vs wattmeter under load condition

Time	Laptop charger			Magic Com			Motor		
	PZEM (W)	Wattmeter (W)	%Error	PZEM (W)	Wattmeter (W)	%Error	PZEM (W)	Wattmeter (W)	%Error
06:00-06:58	12.77 ± 0.09	12.80 ± 0.00	0.2344	64.55 ± 0.51	66.82 ± 0.39	3.3972	106.80 ± 5.80	105.85 ± 5.56	0.8975
09:00-09:58	11.71 ± 1.52	11.90 ± 1.62	1.5966	55.12 ± 0.70	57.33 ± 0.68	3.8549	76.88 ± 2.19	76.13 ± 2.36	0.9852
13:00-13:58	6.51 ± 2.25	6.65 ± 2.25	2.1053	55.48 ± 0.98	57.99 ± 0.53	4.3283	74.94 ± 3.13	75.03 ± 2.93	0.1200
20:00-20:58	12.89 ± 0.11	13.01 ± 0.14	0.9224	65.90 ± 0.54	68.16 ± 0.72	3.3157	103.86 ± 3.97	104.62 ± 3.82	0.7264

Note: Values are presented as mean ± standard deviation (SD) based on 10 measurements recorded at 2-minute intervals.

Table 6 reports the corresponding power measurements for the same three loads and time windows. Power values recorded by the PZEM-004T ranged from 6.51 to 12.89 W for the charger (wattmeter: 6.65-13.01 W), 55.12-65.90 W for the rice cooker (wattmeter: 57.33-68.16 W), and 74.94-106.80 W for the motor (wattmeter: 75.03-105.85 W). Errors ranged from 0.23% to 2.11% for the charger, 3.32% to 4.33% for the rice cooker-the largest deviation recorded among all six tables-and 0.12% to 0.99% for the motor, all still well under the 5% limit. This confirms that the sensor's power measurement remains accurate even as load type and magnitude vary.

Table 7. Energy measurement results of PZEM-004T vs wattmeter under load condition

Time	Laptop charger			Magic Com			Motor		
	PZEM (kWh)	Wattmeter (kWh)	%Error	PZEM (kWh)	Wattmeter (kWh)	%Error	PZEM (kWh)	Wattmeter (kWh)	%Error
06:00-06:58	0.004	0.004	0.0000	0.020	0.020	0.0000	0.031	0.031	0.0000
09:00-09:58	0.003	0.003	0.0000	0.016	0.016	0.0000	0.022	0.022	0.0000
13:00-13:58	0.002	0.002	0.0000	0.017	0.017	0.0000	0.025	0.025	0.0000
20:00-20:58	0.004	0.004	0.0000	0.020	0.020	0.0000	0.031	0.031	0.0000

Table 7 presents the energy measurement results, obtained by having both instruments log the same load simultaneously. The PZEM-004T matched the wattmeter exactly at every time window and load, giving a 0% error throughout: 0.002-0.004 kWh for the laptop charger, 0.016-0.020 kWh for the rice cooker, and 0.022-0.031 kWh for the motor. Such identical readings at this measurement resolution indicate that the sensor's energy accumulation function performs reliably under the tested conditions.

Table 8. Frequency measurement results of PZEM-004T vs wattmeter under load condition

Time	Laptop charger			Magic Com			Motor		
	PZEM (Hz)	Wattmeter (Hz)	%Error	PZEM (Hz)	Wattmeter (Hz)	%Error	PZEM (Hz)	Wattmeter (Hz)	%Error
06:00-06:58	50 ± 0.00	50 ± 0.00	0.0000	50 ± 0.00	50 ± 0.00	0.0000	50 ± 0.00	50 ± 0.00	0.0000
09:00-09:58	50 ± 0.00	50 ± 0.00	0.0000	50 ± 0.00	50 ± 0.00	0.0000	50 ± 0.00	50 ± 0.00	0.0000
13:00-13:58	50 ± 0.00	50 ± 0.00	0.0000	50 ± 0.00	50 ± 0.00	0.0000	50 ± 0.00	50 ± 0.00	0.0000
20:00-20:58	50 ± 0.00	50 ± 0.00	0.0000	50 ± 0.00	50 ± 0.00	0.0000	50 ± 0.00	50 ± 0.00	0.0000

Note: Values are presented as mean ± standard deviation (SD) based on 10 measurements recorded at 2-minute intervals.

Frequency results, shown in Table 8, were equally consistent. Both the PZEM-004T and the wattmeter recorded a steady 50 Hz with zero standard deviation across all loads and time windows, yielding a 0% error rate throughout. This uniformity reflects the stability of the grid supply during testing rather than any limitation of the instruments, and confirms that the PZEM-004T reproduces frequency readings with no measurable drift.

Table 9. Power Factor measurement results of PZEM-004T vs wattmeter under load condition

Waktu	Laptop charger			Magic Com			Motor		
	PZEM (cos φ)	Wattmeter (cos φ)	%Error	PZEM (cosφ)	Wattmeter (cos φ)	%Error	PZEM (cos φ)	Wattmeter (cos φ)	%Error
06:00-06:58	0.544 ± 0.0070	0.562 ± 0.0092	3.2028	1.000 ± 0.0000	1.000 ± 0.0000	0.0000	0.444 ± 0.0084	0.431 ± 0.0099	3.0162
09:00-09:58	0.547 ± 0.0134	0.551 ± 0.0173	0.7260	1.000 ± 0.0000	1.000 ± 0.0000	0.0000	0.470 ± 0.0067	0.458 ± 0.0063	2.6201
13:00-13:58	0.478 ± 0.0418	0.471 ± 0.0362	1.0352	1.000 ± 0.0000	1.000 ± 0.0000	0.0000	0.471 ± 0.0088	0.454 ± 0.0070	3.7445
20:00-20:58	0.551 ± 0.0074	0.562 ± 0.0103	1.9573	1.000 ± 0.0000	1.000 ± 0.0000	0.0000	0.449 ± 0.0088	0.433 ± 0.0095	3.6952

Note: Values are presented as mean ± standard deviation (SD) based on 10 measurements recorded at 2-minute intervals.

Power factor, the final parameter examined, is summarized in Table 9, where agreement between the two instruments varied more noticeably by load type. For the laptop charger, PZEM-004T readings of 0.478-0.551 compared with 0.471-0.562 on the wattmeter produced errors of 0.73%-3.20%; the motor showed a similar spread, with PZEM-004T values of 0.444-0.471 against 0.431-0.458 on the wattmeter yielding errors of 2.62%-3.74%. The rice cooker was the outlier in the other direction, with both instruments holding steady at a power factor of 1,000 (SD = 0,0000) and 0% error across all four time windows. Although the laptop charger and motor-both non-resistive loads-showed somewhat larger fluctuations than the purely resistive rice cooker, every recorded error remained well inside the 5% tolerance, confirming acceptable power factor accuracy across the range of load characteristics tested.

4.2 Relay Response Time Testing

The relay response time testing aims to determine the responsiveness of the system to the control features implemented in the device. The testing was conducted by measuring the time required from the initiation of a control command or triggering condition until the relay changed its state. The tested control features included ON/OFF control, energy limit, power limit, on-duration (timer), and scheduled ON/OFF time.

Table 10. Relay response time test results based on feature

Control Feature	Load	ON Response Time (s)	OFF Response Time (s)
ON/OFF	LED Lamp	0.246	0.242
ON/OFF	Fan	0.300	0.300
Energy Limit	LED Lamp	–	1.396
Energy Limit	Fan	–	0.968
Power Limit	LED Lamp	–	0.692
Power Limit	Fan	–	0.748
On Duration (Timer)	LED Lamp	–	0.844
On Duration (Timer)	Fan	–	0.922
Scheduled ON/OFF Time	LED Lamp	0.786	0.880
Scheduled ON/OFF Time	Fan	0.724	0.776

The relay response time test results for the control features implemented in the system are presented in Table 10. The response times vary depending on the control feature and load. The fastest response time was 0.242 s for the OFF command of the ON/OFF control feature with the LED lamp, while the longest response time was 1.396 s for the energy limit control feature with the LED lamp. For the ON/OFF control feature, the response times ranged from 0.242 to 0.300 s for the OFF command and from 0.246 to 0.300 s for the ON command. The energy limit, power limit, and on-duration control features were designed to automatically turn off the load when the corresponding condition or limit was reached, resulting in response times ranging from 0.692 to 1.396 s. Meanwhile, the scheduled ON/OFF feature showed response times ranging from 0.724 to 0.786 s for the ON command and from 0.776 to 0.880 s for the OFF command.

According to the Songle 5 V relay datasheet, the operation time (maximum activation time) of the relay is 10 ms (0.010 s), while the release time is 5 ms (0.005 s) [21]. These specifications represent the response of the relay itself under the conditions specified in the datasheet and do not include communication and processing delays associated with an IoT-based control system. In contrast, the response time measured in this study represents the overall process from the initiation of a control command or triggering condition until the relay responds. This process involves data processing by the ESP32 and, for remote control features, data communication through the IoT network before the command reaches the relay. Therefore, the response times obtained in this study are longer than the mechanical response times specified in the relay datasheet. Thus, the measured response time should be interpreted as the overall latency of the IoT-based control system rather than the mechanical response time of the relay alone.

4.3 System Reliability Testing

The system reliability testing aims to evaluate the consistency of the system in controlling the electrical energy consumption of the loads. In this study, reliability refers to the system's ability to consistently enforce the specified daily energy consumption limit for each load over an extended period without failure to disconnect the load when

the limit is reached. The reliability evaluation is based on the system's successful operation throughout the two-week testing period, while the reduction in energy consumption is evaluated separately as an indicator of the system's energy-saving effectiveness. This testing was carried out over two weeks: one week to determine the load's electrical energy usage before using the system, and one week after using the system. The control feature and loads used in this testing are the energy limit control feature, along with an LED lamp and a fan.

Table 11. System reliability test results

No	Date	Before system (kWh)		Date	After system (kWh)	
		LED lamp	Fan		LED lamp	Fan
1	15/04/26	0.098	0.180	22/04/26	0.068	0.108
2	16/04/26	0.099	0.103	23/04/26	0.068	0.108
3	17/04/26	0.085	0.218	24/04/26	0.068	0.108
4	18/04/26	0.089	0.181	25/04/26	0.068	0.108
5	19/04/26	0.098	0.129	26/04/26	0.068	0.108
6	20/04/26	0.091	0.127	27/04/26	0.068	0.108
7	21/04/26	0.130	0.155	28/04/26	0.068	0.108
Total (kWh)		0.690	1.093	Total (kWh)	0.476	0.756

The test results are presented in Table 11. The results show that the electrical energy consumption of the tested loads decreased after implementing the system. For the LED lamp, the total energy consumption decreased by 0.214 kWh, from 0.690 kWh before system implementation to 0.476 kWh after system implementation, representing a reduction of 31.01%. For the fan, the total energy consumption decreased by 0.337 kWh, from 1.093 kWh to 0.756 kWh, representing a reduction of 30.83% over the one-week testing period. These results demonstrate the effectiveness of the developed system in reducing the electrical energy consumption of the tested loads through the implementation of the energy limit control feature. Throughout the two-week testing period, the system consistently enforced the daily energy limit for both loads without failure, indicating that the system is reliable in controlling electrical energy usage, with the resulting energy savings of 31.01% and 30.83% serving as the quantitative measure of this reliable performance.

5 Conclusion

Based on the results of the study, it can be concluded that the IoT-based electrical energy consumption monitoring system is able to provide good measurement accuracy of electrical load parameters across all variations of time, load type, and load capacity used, with a maximum error percentage of 4.3%, which does not exceed the maximum threshold of 5%. The designed system successfully achieved a normal relay response time, with the fastest response time occurring in the ON/OFF control feature at 0.242–0.300 seconds and the longest in the energy limit control feature at 0.968–1.396 seconds. The system also demonstrated reliable performance in consistently enforcing the daily energy consumption limit for each load throughout the two-week testing period, without failure in disconnecting the load once the limit was reached. The implementation of the energy limit control reduced electrical energy consumption by 31.01% for the LED lamp load and 30.83% for the fan load over the one-week testing period. The novelty of this study lies in the integration of varied testing conditions, including different testing times, load types, and load capacities, with an IoT-based automatic and remote load-control mechanism, together with an extended reliability evaluation for limiting electrical energy consumption.

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