

IoT based smart home system design for real time control of household electrical devices

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ABSTRACT

The development of Internet of Things (IoT) technology has fostered the emergence of smart home concepts that enhance efficiency and convenience in controlling household electrical appliances. This study presents the design of a smart home system based on the ESP32 microcontroller integrated with a relay module to control electrical devices either locally via a TFT ILI9341 touchscreen display or remotely through a Node-RED dashboard using the MQTT protocol. The system is equipped with a PZEM-004T sensor to measure electrical parameters and a DHT11 sensor to monitor temperature and humidity, with real-time data visualization provided on both the touchscreen and the IoT dashboard. Experimental results demonstrate that the system delivers fast response control, reliable monitoring accuracy, and supports household energy efficiency by enabling more effective electricity consumption monitoring.

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1. INTRODUCTION

Household electricity demand in Indonesia continues to experience a significant increase each year. According to projections from the Directorate General of Electricity, Ministry of Energy and Mineral Resources (ESDM), the number of household customers connected to the PLN network is expected to exceed 70 million by 2025. In line with this, national electricity consumption in 2024 is projected to reach 120,000 GWh [1]-[4]. This surge is driven by the increased use of electronic devices and changes in lifestyle, particularly in urban areas. Most of the electricity consumption comes from household appliances such as refrigerators, televisions, washing machines, lighting, and air conditioners. However, many household users do not fully understand the power consumption of each device, resulting in electricity bills that often increase without the exact cause being known [5]-[10].

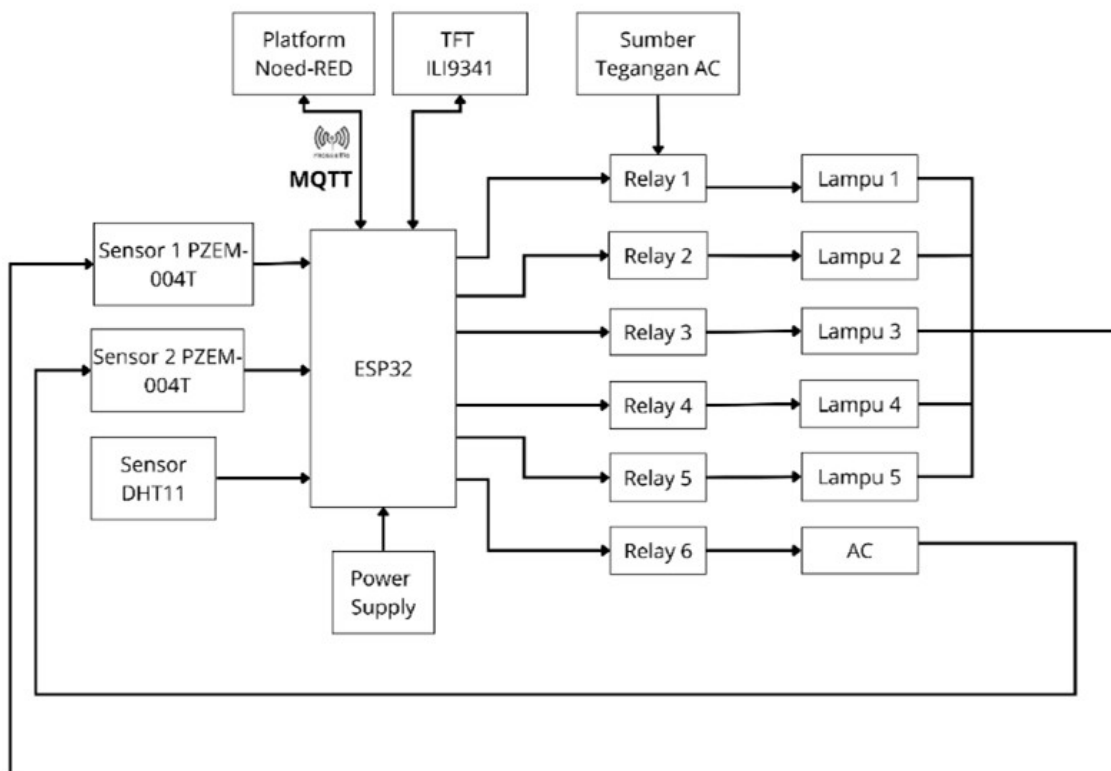
The amount of electricity consumption is not solely determined by the power rating of a device, but also by the duration of its use. Low-power devices used for long periods can consume more energy compared to high-power devices used briefly [11]. Over the past two decades, the development of Internet of Things (IoT) technology has introduced the concept of smart homes, which can integrate various household appliances within a single network. This technology allows devices to be monitored and controlled in real-time via the internet. In addition to enhancing comfort and security, smart homes also offer a smart approach to managing electricity consumption more efficiently and measurably [12]-[15].

One energy-saving solution is the implementation of a real-time household device control system, particularly for lighting and air conditioning. By integrating the Node-RED platform, users can control devices remotely via the internet while also creating automated operation logic. Node-RED, based on flow programming, simplifies the design of IoT applications because it is intuitive and does not require complex coding [16]-[20]. Controlling devices such as air conditioners is crucial because these appliances significantly contribute to household energy consumption [21]. In addition to remote control, the system is equipped with

local monitoring via a TFT touchscreen, allowing users to directly observe voltage, current, power, and room temperature conditions. Consequently, users become more energy-aware and can take proactive steps to save electricity. The design of an IoT-based smart home system using the ESP32 microcontroller as the central controller combines two main functions: control and monitoring. The system facilitates the management of household electrical devices both manually via the TFT and online through Node-RED. Moreover, real-time monitoring of electrical parameters and room temperature helps users make data-driven decisions. With these capabilities, the system is relevant and has strong potential for application as a means to improve energy efficiency while providing comfort in daily life.

2. METHOD

The research methodology serves as a guide in carrying out each stage of the study to ensure that the results obtained align with the objectives. This study employs a Research and Development (R&D) approach, as it not only focuses on data collection but also on the process of designing and producing a smart home system prototype. The R&D stages include problem identification, design, development, and prototype testing. Through this approach, the research is expected to produce an IoT-based household device monitoring and control system that can not only be performance-tested but also contribute to improving the efficiency of electricity usage in households. A block diagram is a graphical representation that shows the relationships between the main components of a system in a simple and structured manner. Block diagrams are used to illustrate the working concept of a system or project being developed. The use of block diagrams helps explain the system more clearly and systematically, making it easier for readers to understand the workflow without having to examine complex technical details.



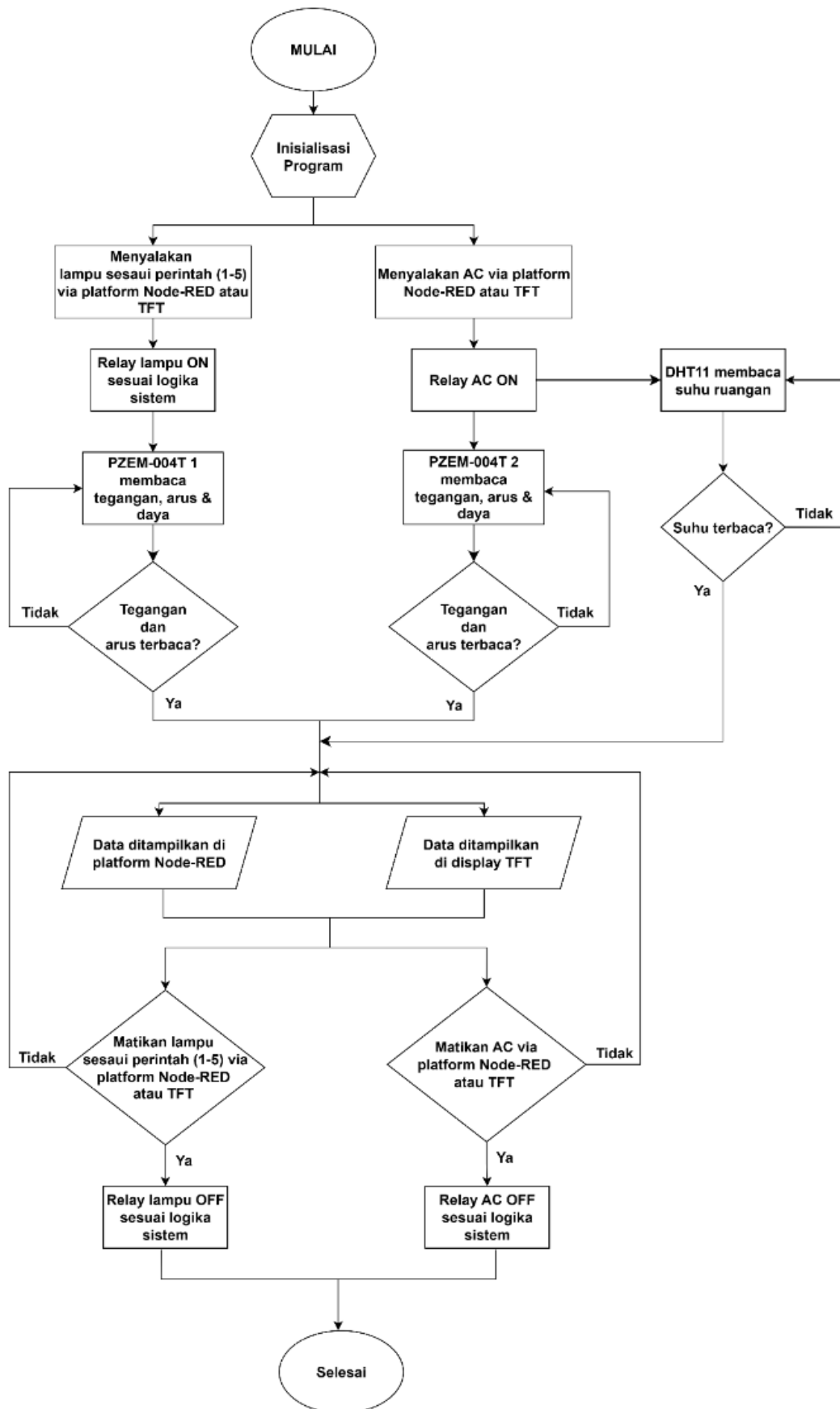


Figure 2. Flowchart

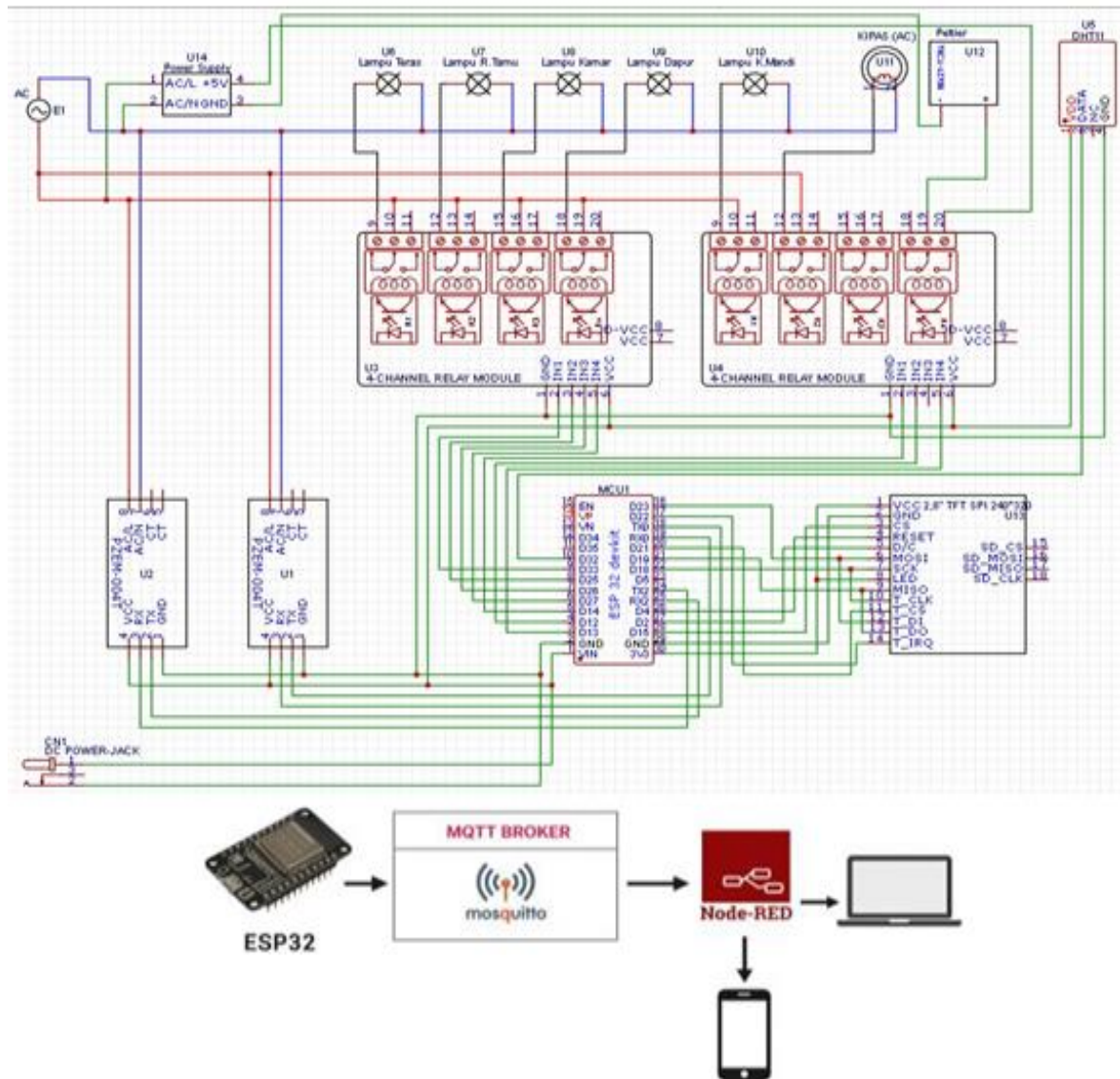


Figure 3. Circuit diagram of proposed system

A circuit diagram ensures that all components are properly connected to one another so that the system can function according to their respective roles. In creating a circuit diagram, each component can be depicted in its actual form or represented by a symbol.

The working principle of this device is as follows: on the TFT and Node-RED platform, there are ON/OFF buttons for the lights and AC (Peltier). Users can turn the lights and AC (Peltier) on or off through either of these interfaces. When the ON/OFF button is pressed, the relay activates to connect the electrical current, causing the lights and AC (Peltier) to turn on. Once the lights and AC (Peltier) are on, the PZEM-004T sensor measures voltage, current, and power, then sends this data to the ESP32 to be displayed on both the TFT and Node-RED platform. Additionally, a DHT11 sensor measures the room temperature and sends the readings to the ESP32 to be displayed on the same interfaces.

The component box containing the main circuitry includes the ESP32, PZEM-004T sensor, DHT11 sensor, relay module, and TFT display module. This box is designed to organize the components neatly, provide protection, and facilitate maintenance or future system development. The prototype design was carried out by creating a miniature house as a representation of the smart home system being developed, with dimensions of 60×60 cm, adapting the type 36 house model. This miniature house serves to illustrate the positions and functions of the controllable electrical devices, such as lights and air conditioners, thereby facilitating the simulation process. Figure 4 and 5 show the hardware design and component box design.

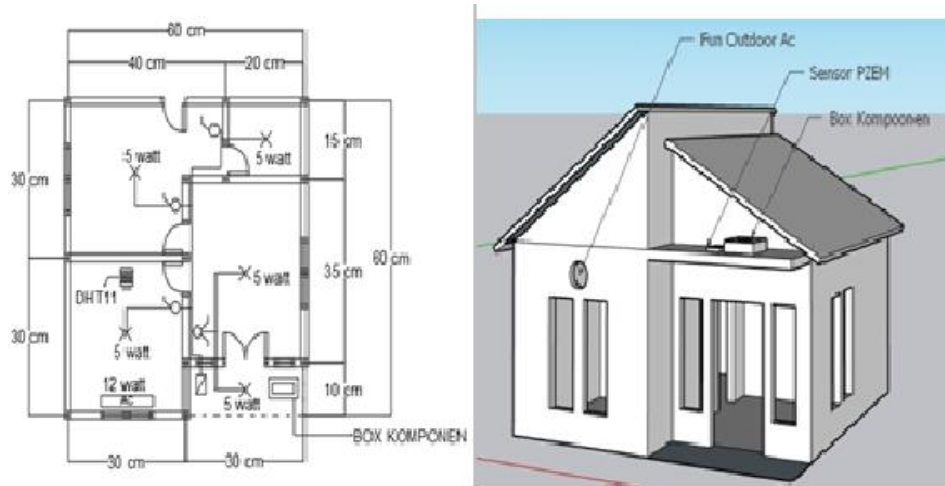


Figure 4. Hardware design

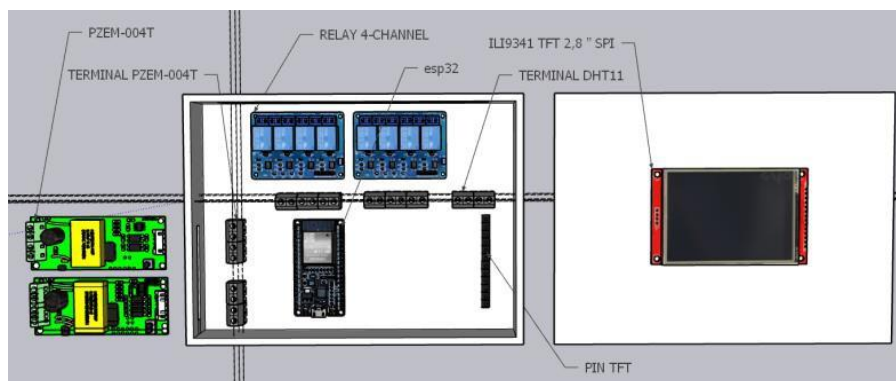


Figure 5. Component box design

The control and monitoring programming in this final project, which focuses on an IoT-based smart home system, is carried out using the Arduino IDE (Integrated Development Environment) application. Arduino IDE is software used to write, upload, and manage programs on microcontroller boards such as the ESP32. The programs created in Arduino IDE are known as “sketches” or source codes, using a specific file format designed to control devices and execute system logic automatically. Node-RED serves as the communication hub between sensors, actuators, and the user interface, with a node palette on the left, a workspace in the center for arranging connection flows, and an information panel on the right. Input nodes receive data from devices such as the ESP32, while output nodes send commands to actuators like relays or lights. This approach provides high flexibility, as the logic flow can be easily modified or expanded simply by adding or connecting new nodes [22].

3. RESULTS AND DISCUSSION

This section presents the implementation results of the hardware and software of the designed smart home system, as well as an analysis of the tests conducted to evaluate the system’s functionality, performance, and reliability. The dashboard can be accessed via both smartphone and PC since it is web-based, providing users with high flexibility in operating the system. The dashboard displays several components, including ON/OFF push-buttons for controlling lights via relays, status indicators in the form of text or virtual LEDs, and monitoring graphs showing sensor data such as temperature, humidity, and electrical parameters (voltage, current, power, energy, frequency, and power factor) in real-time. The smartphone interface is designed to be simple and responsive for ease of use, as shown in Figure 6, while the PC dashboard offers a wider layout, allowing all information to be viewed comprehensively on a single screen, as seen in Figure 7 below. With this dashboard, the smart home system can be controlled and monitored from anywhere as long as the devices are connected to the internet.



Figure 6. Dashboard display on PC



Figure 7. Dashboard display on smartphone

The functional testing stage is carried out to ensure that all system components operate according to their designed functions. At this stage, the ESP32 is tested to control all components, including turning relays on or off, reading data from the DHT11 and PZEM-004T sensors, and displaying information on the SPI TFT ILI9341 screen. The test results indicate that all components function well in an integrated manner. The relay responds to ON/OFF commands according to the input, the DHT11 sensor provides stable temperature and humidity data, the PZEM-004T sensor accurately displays electrical parameters, and the TFT clearly shows all information in real-time. Monitoring testing is conducted to ensure that the data sent by the system can be accurately displayed and monitored by the user in real-time. At this stage, the ESP32 microcontroller sends data from the DHT11 sensor (temperature and humidity) and the PZEM-004T sensor (V, I, P, E, F, PF) to the Node-RED software via MQTT communication, as well as to the TFT ILI9341 display. In the Node-RED IoT platform, the incoming data is visualized on a dashboard containing relay status indicators, temperature and humidity gauges, and gauges for displaying electrical parameters.

The test results show that Node-RED is able to receive data from the ESP32 smoothly, without any significant interruptions or delays. Changes in sensor conditions are immediately reflected on the dashboard, such as room temperature variations or when electrical loads are activated via the relay. In addition, the relay indicators on Node-RED respond accurately according to the actual conditions of the hardware. Similarly, the TFT ILI9341 display receives data from the ESP32 without disruption or delay. Changes in sensor conditions are instantly visible on the TFT screen. Both the IoT-based and local monitoring system using the TFT function as expected, making it easy for users to supervise the system either at home or remotely.

Relay testing is conducted to ensure that all six relays used in the system function properly, both through direct control from the local TFT and via the IoT Node-RED platform from three different locations: Padang, Baso, and Karawang. This testing includes on/off scenarios for each relay, with the actual response and system response time recorded for evaluation. Based on the results in Table 1, all relays (Relay 1–6) can be effectively controlled via the Node-RED dashboard from multiple locations. Each relay responds to ON and OFF commands quickly, with an average response time of approximately ± 0.1 seconds in Padang, ± 0.2 seconds in Baso, and ± 0.2 seconds in Karawang, indicating no significant delays. This demonstrates that remote relay control operates stably and as designed. Any observed differences may be caused by unstable internet connections; the greater the distance and variability in network quality, the longer the potential delay. Nevertheless, these differences remain within acceptable limits and do not interfere with the monitoring process.

Table 1. Relay response from multiple locations

Relay	Padang		Baso		Karawang	
	Delay (s)		Delay (s)		Delay (s)	
	ON	OFF	ON	OFF	ON	OFF
Relay 1	0.1	0.1	0.28	0.25	0.21	0.19
Relay 2	0.1	0.1	0.2	0.22	0.24	0.2
Relay 3	0.1	0.1	0.21	0.1	0.18	0.15
Relay 4	0.1	0.1	0.2	0.19	0.23	0.19
Relay 5	0.1	0.1	0.17	0.15	0.16	0.21
Relay 6	0.1	0.1	0.25	0.26	0.25	0.19

This test was conducted by comparing the sensor readings displayed on the TFT with the data received through Node-RED from three different locations: Padang, Baso, and Karawang. The purpose of this test is to determine whether there are any differences in values when data is transmitted over the internet to various locations. The test results show that the data displayed on the TFT closely matches the data shown on Node-RED (IoT) across the three different locations. Minor differences in voltage, current, power, energy, frequency, and PF remain within the sensor's measurement tolerance ($\pm 1-2\%$). This demonstrates that the monitoring system can transmit data accurately to multiple locations via the IoT platform without significant changes in values. This test is conducted to evaluate the accuracy of the PZEM-004T sensor by comparing the measurements of electrical parameters (voltage, current, power, energy, frequency, and PF) recorded by the sensor with the results obtained from standard measuring instruments. The purpose of this method is to ensure that the sensor can be used reliably in the monitoring system, particularly when the electrical load varies. The test results can be seen in Table 2.

Table 2. Sensor testing

Load	Voltage (V)			Current (A)			Power (W)	
	Sensor	Instrument	Er %	Sensor	Instrument	Er %	Sensor	Spec.
1 Lamp (5W)	234.40	235	0.2	0.10	0.08	25	4.	5
2 Lamp (10W)	234.40	235	0.2	0.20	0.17	17	9.	1
3 Lamp (15W)	234.70	235	0.1	0.31	0.26	19	13.8	1
4 Lamp (20W)	234.90	235	0.04	0.41	0.35	17	18.5	2
5 Lamp (25W)	234.80	235	0.08	0.51	0.45	13	23.1	2
AC (12W)	233.30	235	0.2	0.09	0.07	28	17.1	1

From the test data above, first, the voltage measurements from the sensor compared to the measuring instrument show a very small difference, averaging only around $\pm 0.1-0.2$ V, with an average error percentage of $\leq 0.2\%$. Second, the current measurements from the sensor compared to the measuring instrument show a more significant difference than voltage. The percentage error reaches 13–28%, which occurs because the reference current values are very low, resulting in a small absolute difference but a high

percentage error. However, as the current load increases, the sensor's accuracy improves. For power measurements, the sensor readings are compared with the power specified by the device. As shown in Table 2, the average difference between the sensor-measured power and the device's specified power is approximately ± 1.0 W. However, for the air conditioner (AC), there is a relatively significant difference, with the sensor readings being higher than the component's specified power. This may be caused by the influence of the power factor or the inherent tolerance of the PZEM sensor itself.

4. CONCLUSION

Based on the design and implementation results, this study successfully developed an Internet of Things (IoT)-based smart home system capable of controlling household electrical devices in real-time. The system can be operated locally via a touch-interface TFT display and remotely through the Node-RED dashboard connected to the internet. Test results show that the control process works effectively, with electrical devices being turned on or off according to user commands without noticeable delays. This demonstrates that the system design meets the requirements for flexibility and ease of household device control under various conditions. In addition to control functions, this study also successfully designed a real-time monitoring system for electricity consumption and room temperature. Using the PZEM-004T and DHT11 sensors, electrical parameters such as voltage, current, power, energy, frequency, and power factor can be monitored accurately. This information is displayed directly on the TFT display and Node-RED dashboard, allowing users to gain a comprehensive view of energy consumption. The presence of this monitoring feature adds significant value, helping users understand energy usage patterns and potentially supporting household electricity savings. Overall, the results demonstrate that the designed smart home system is capable not only of controlling electrical devices through two different pathways (local and remote) but also of providing easy, real-time energy monitoring. Therefore, this system offers an innovative solution to enhance comfort, energy efficiency, and the implementation of smart home concepts in residential settings. This success also proves that the application of IoT in smart homes has great potential for further development, including aspects of scalability, data security, and integration with other smart devices.

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