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# IoT-Based Smart Plug with Real-Time Energy Measurement Optimization and Adaptive Current Cutoff

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**Abstract**

The use of electrical energy as a primary power source is increasing, with the residential sector being one of the largest consumers. Electrical energy expenditure often occurs accidentally, potentially leading to energy waste. This research develops an IoT-based electricity usage monitoring system to minimize electrical energy waste and help users improve efficiency and protection against voltage spikes using the R&D approach with a waterfall model. There are 3 layers of IoT architecture using the PZEM-004T sensor as a measuring device for electrical parameters and ESP8266 as a communication module where the results of the sensor readings will be displayed in real-time on the LCD and Blynk with a time difference of 1.6 seconds, in addition to the cost indicator, and the current flowing conditions are also displayed. Sensor readings are valid with values < ± 0.5% for current and voltage and < ± 1% for power readings. System monitoring tests were carried out on 10 electronic devices, and the results of the estimated electricity costs from the use of electrical energy of these electronic devices were obtained. The system is also equipped with a protection feature displayed with a warning indicator, where if the current exceeds 3.1A, the power will automatically be cut off within 15 seconds. This system provides a solution to the efficiency of electrical energy expenditure and provides more protection.

**Keywords:** Smart plug, monitoring system, Internet of Things, electrical energy, warning indicators.

## I. INTRODUCTION

The rapid advancement of technology has led to an increased demand for electrical energy as a primary resource [1]. People spend 90% of their time indoors when they are not busy, relying on electricity for most of their activities such as lighting and air conditioning for comfort [2] . In addition, electrical energy expenditure is often done unintentionally, such as leaving an electronic device that is no longer used in a lit condition and other expenses that occur unconsciously [3], [4]. This caused the number of electricity consumers in the residential sector to increase; in addition to that, it can result in the potential for fire [3], [5]. According to the Ministry of Energy and Mineral Resources report, one of the sectors that consume the most electrical energy is the residential sector, where the increase in electricity consumption in 2022 reached 7,92% compared to the previous year [6].

An innovation that can be used is the development of smart devices that can effectively monitor and control energy use [7], [8]. This enables the monitoring of potential electrical faults for early identification and treatment before they become fatal faults, such as fire [9]. Of the various smart devices that can utilize energy, smart plugs can be a practical and easy-to-implement solution to improve the efficiency of electricity usage and protection [10].

Smart plugs enable users to control and monitor the electricity consumption of connected devices through smartphone or computer applications and can provide current limitation to the system [11]. With the ability to measure power usage in real-time, smart plugs can provide accurate information on electricity consumption and cost expenditure from the power flowing [12] , therefore reducing the expenditure of electrical energy from being wasted and reducing wasteful costs that must be paid and can reduce the risk of unwanted current surges [13] . Researchers have explored the design of plug sockets as electrical energy usage management devices, which offer a variety of features. Table 1 summarizes the researchers' contributions to smart plug design and implementation.

Elorbany et al. [14] designed and implemented a smart socket for monitoring electrical energy. This system uses Wi-Fi to monitor electrical energy consumption values in real time. Tastan presented a solution of his energy management system design that can control and monitor devices using Blynk [15]. The results were able to schedule device operations at certain times and reduce electricity consumption by 20%, but the system testing is only carried out for four devices. The development of a household energy

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TABLE 1
COMPARISON TABLE OF EXISTING SMART PLUG SYSTEMS

| References | Software | Hardware | | Output Jack | Feature | Limitations |
|---|---|---|---|---|---|---|
| | | Microcontroller | sensor | | | |
| Elorbany et al. [14] | - Mobile Application<br>- Firebase Cloud Platform | - Wemos D1 Mini | - ACS712 | 1 | - Real-time monitoring and historical<br>- Overcurrent protection | - No indicator of tariff energy consumption.<br>- Only to monitor current consumption. |
| Tastan [15] | - Blynk | - Arduino Pro Mini<br>- NodeMCU | - ACS712<br>- ZMPT101B | 1 | - Energy usage scheduling<br>- Provide a usage report | - Limited devices that can be controlled. |
| Wonohadidjojo et al. [16] | - Mobile Application<br>- Firebase Cloud Platform | - NodeMCU<br>- Arduino Uno R3 | - ACS712<br>- ZMPT101B | 1 | - Monitoring electronic devices<br>- Controlling the on/off system through the app | - Limited monitoring and control distance.<br>- Safety Problem. |
| Satya et al. [17] | - Arduino IDE | - Arduino Kit | - ACS712 | 1 | - Design a system to monitor current consumption | - Only measures electric current. |
| TP-Link [18] | - Smartphone App | | | 1 | - Scheduling on/off connected devices<br>- Perform voice control | - Energy monitoring reports are not provided. |

management system has been carried out by Wonohadidjojo et al. [16]. The designed system allows users to monitor and control electronic devices in real-time via smartphones using Firebase as a database.

The design of an electric current monitoring system carried out by satya et al. [17] has a current measurement accuracy of the ACS712 sensor which has been compared using a standard clampmeter measuring device with results above 75% with an uncertainty level of around 14.14% to 24.83%, further testing needs to be done to improve the accuracy of current measurements. This system is also not provided with a maximum current limit, so it will be vulnerable to system damage if the current flowing is large. The commercial smart plug device developed by TP-Link features device scheduling and can give voice commands, but there is no monitoring report of the energy used and no warning notifications [18].

From these several studies, there are still shortcomings in reading values that are not optimal but still tolerable and do not have protection features in the system. In addition, the system is designed for small home voltages. Several smart plugs in the market do not provide an integrated system of real-time monitoring and control, overcurrent protection features, data analysis, electrical energy usage cost indicators, and alert notifications to mobile devices in one cost-effective and easy-to-implement design [19]. Therefore, a system that can be able to do this is needed [20].

This research develops an IoT-based smart plug system that can measure and monitor electrical energy consumption in real-time for energy expenditure efficiency and electricity costs, display the cost of using electrical energy, load control, and provide protection against overcurrent with several scenarios in the system to optimize the safety element and prevent damage due to current surges. The system uses sensors with a maximum reading accuracy level of electrical energy, and the results of sensor readings are displayed through Blynk. Both will be interconnected to display electrical measurement parameters, including voltage, current, power, and frequency values, as well as cost indicators and warnings to indicate whether or not the flowing current exceeds the set limit. In order to minimize the waste of electrical energy, this system is designed to help users increase the efficiency of electrical energy expenditure and provide more security against potential surges (electrical protection).

## II. METHOD

The research process begins by conducting a literature study to identify the concept of the designed system, which is then carried out in the design stage, including both IoT architecture design, hardware design, and software design in making the developed system. which has been processed using the Blynk platform. Parameter reading data will be collected on the Blynk cloud server, which can be downloaded and analyzed.

### A. Architecture System Smart Plug

The design of the prototype smart plug as a monitoring and protection system for electricity use is divided into three main layers: the perception layer, the network layer and the application layer [21]. The perception layer consists of sensors and actuators to perform actions in turning on and off the system and obtaining electrical usage data [22], [23]. The data obtained are then sent to the network layer to be collected, which will then be transmitted to the next layer. The data sent are then displayed on the application dashboard called the application layer. The system design of each layer is illustrated in Figure 1.

To validate the needs of the IoT architecture, prototypes are designed, built, and then evaluated to find out that the design made is as expected. The perception layer uses relays to act as turning the system on and off and PZEM-004T sensors that can calculate the value of electrical parameters of the AC voltage, including current (A), voltage (V), real power (W), frequency (Hz) and power factor (PF) [24]. The value of the reading of the electric power parameter will be calculated using the price equation in Equation 1 to see the use of the price of the flowing power [25] :

$$Cost = kWh \,.\, Electricity\ tariff\ class \qquad (1)$$

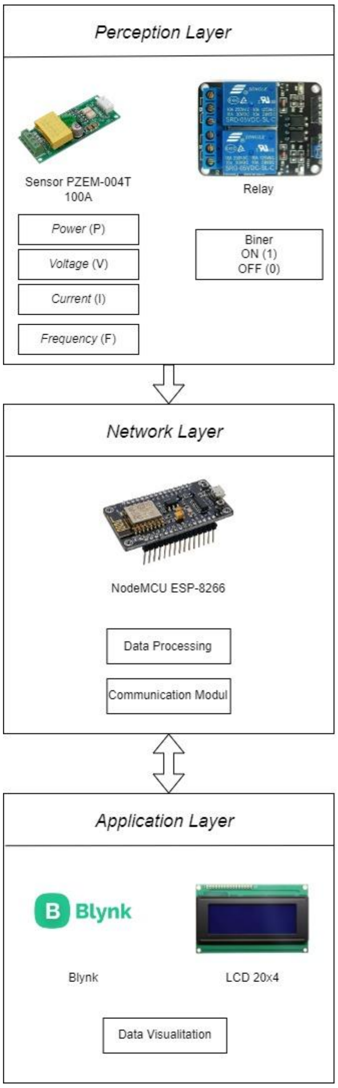



Figure 1. Smart plug block diagram architecture

The data obtained from sensors and relays in the perception layer will be collected by ESP8266 in the network layer for the data transmission process to the next layer to be displayed to the user [26]. Data that have been collected and processed will be visualized in the application layer [27]. The service is used to visualize the data that has been collected in the form of hardware using 20x4 LCD components, and software in the form of applications to utilize the data that have been processed using the Blynk platform.

## B. Design System

The developed monitoring system device consists of a microcontroller and other electronic components such as the module sensor PZEM-004T 100A, relay, power supply, reset button and 20x4 LCD. The microcontroller used is NodeMCU v1 with a CP2102 driver that has a Wi-Fi feature. The hardware design is illustrated in Figure 2.

Two push buttons function to reset the NodeMCU when an error occurs or the system is automatically disconnected and to reset the price displayed on the LCD and Blynk. The push button for system reset is connected to pin D6, while the push button for price reset is connected to pin D7. The PZEM-004T 100A sensor is connected to pin D3 for the RX pin of the sensor and to pin D4 for the TX pin of the sensor. The pin connected to the NodeMCU is a serial pin to exchange data, while the other side of the sensor connects a 220V AC voltage so that the sensor can measure the parameters of power consumption and the relays connected to the load terminals [28]. The developed device will be tested for its function in reading the value of electrical parameters such as current, voltage, and power from electronic devices in the household and can send the data to the IoT platform, that is, Blynk, to conduct monitoring. The smart plug system in this investigation was carried out according to the flow chart shown in Figure 3.

The system will start measuring the current, voltage, and power of AC electricity after the smart plug is connected to the Internet and the electronic load

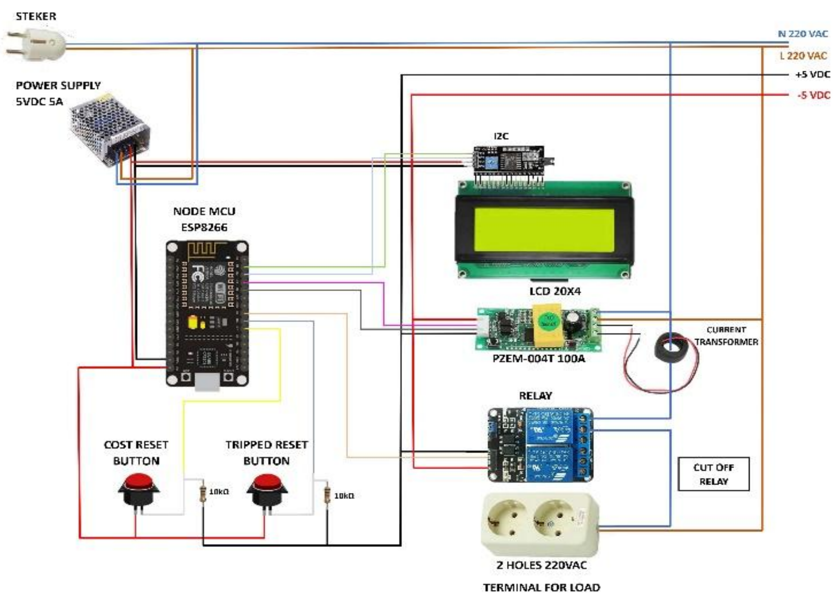



Figure 2. Design hardware system

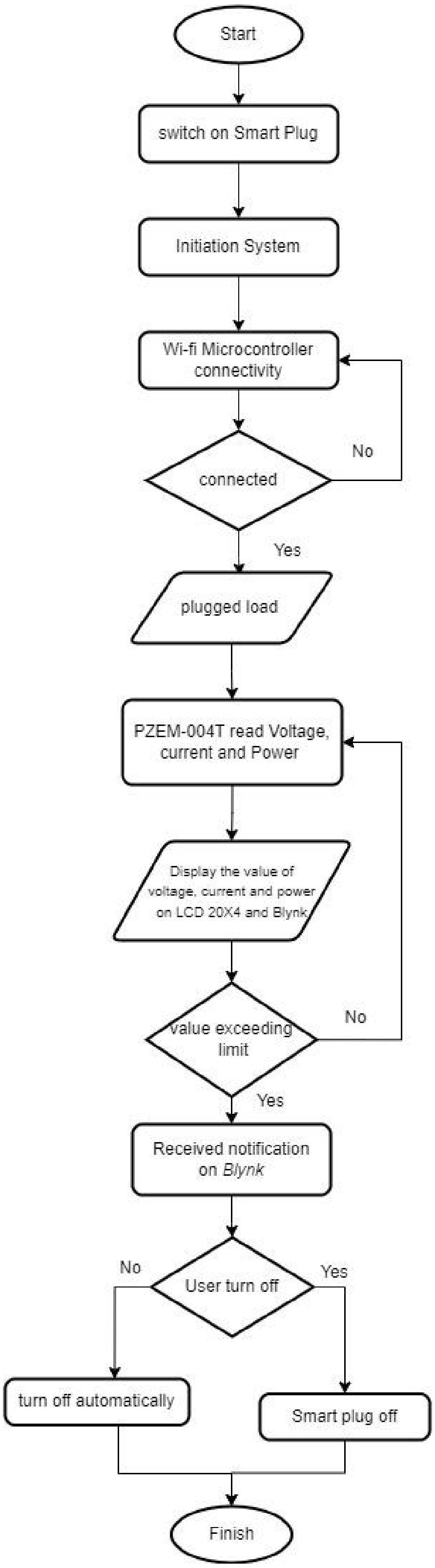



Figure 3. Smart plug flow chart system

is attached to the smart plug [29]. After the measurements are successfully performed, the system displays the measurement parameter values on the LCD and the Blynk platform to monitor the power consumed and the cost produced. To improve system performance, adjustments were made to protection parameters such as maximum current limit, notification time lag, and automatic power cut delay [10]. Adjustments were made through several test scenarios with current variations of 1A, 2A, 3A, and 3.1A to ensure that the system can detect overcurrent values and automatically cut off electricity to protect the device. The system is given a maximum current limit of 3.1A for safety and cost savings; if the current flow exceeds the limit, the smart plug will be automatically disconnected. Setting the current limit is done through programming on the Arduino IDE. Thus, the system can operate stably and provide optimal protection.

## III. Result and Discussion

The designed system has a hardware output and is then integrated into the software so that it becomes a unified smart plug system that can function properly according to the needs and objectives of the research. The results of the system design of the hardware and software dashboard display can be seen in Figure 4 and Figure 5.

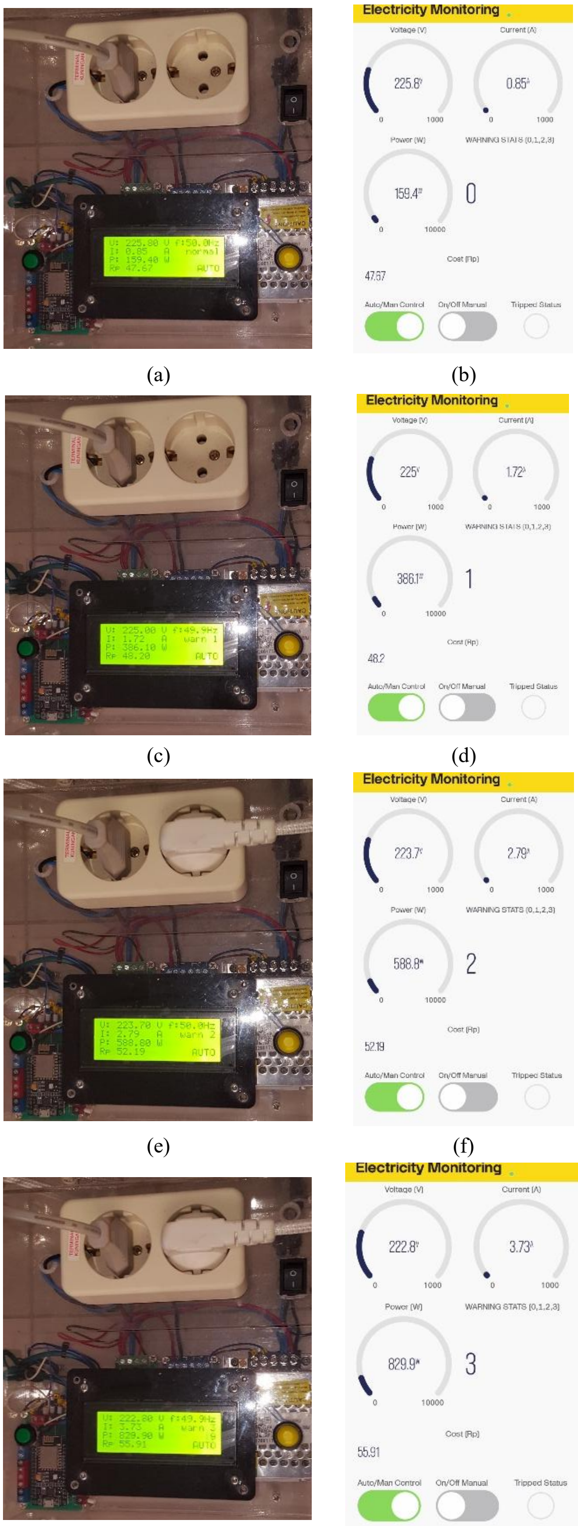
In addition to displaying electrical parameters such as voltage, current, power, and frequency, it also displays the cost of the calculated power usage, relay conditions, and warning indicators. On the hardware display, the relay condition is displayed with the word “Manu” when in manual condition and the word “Auto” when in automatic condition. On the hardware display, warning indicators are displayed with the

Figure 4. Hardware implementation


Figure 5. Dashboard platform monitoring system

words "Normal", "Warn 1", "Warn 2", and "Warn 3" with a description as in Table 2. On the software display or Blynk dashboard, the warning indicator during normal conditions is displayed with the number "0", warning 1 with "1", warning 2 with "2", and warning 3 with "3". The display on hardware and Blynk can be seen in Figure 6.

The Blynk dashboard as a monitoring platform displays three electrical measurement parameters which are voltage, current, and power. It also displays




(a) (b) (c) (d) (e) (f) (g) (h)

Figure 6. Hardware and Blynk display (a)Normal, (b) 0, (c)Warn1, (d) 1, (e)Warn2, (f) 2, (g)Warn3, (h) 3

TABLE 2
INDICATOR WARNING IN HARDWARE AND SOFTWARE

| No | Indicators Definition | Indicators Hardware | Indicators Software | Current Allowed |
|---|---|---|---|---|
| 1 | Normal | Normal | 0 | <1,00A |
| 2 | Warning 1 | Warn 1 | 1 | > 1,10A - ≤ 2,00A |
| 3 | Warning 2 | Warn 2 | 2 | > 2,10A - ≤ 3,00A |
| 4 | Warning 3 | Warn 3 | 3 | > 3,10A |

the cost of electricity usage of electronic devices attached to the smart plug, current usage warning indicators, relay conditions, and system tripped status. When the warning indicator reads '3', the system will automatically disconnect with an interval of 15 seconds when the relay condition is in automatic or auto mode as in Figure 7. On the hardware, when it turns 15 seconds, the LCD will display 'system is tripped', as shown in Figure 8. Setting limits on the system by setting the ampere value because electric current is a parameter that tends to increase drastically when a disturbance occurs such as a short circuit, so that the system can run properly and will automatically disconnect when the ampere exceeds a predetermined limit [30]. The data displayed are real-time.

Data transmission testing was carried out to observe the duration of sending PZEM-004T sensor data from the monitoring device to the Blynk platform. The results can be observed in Table 3.

Research [14] does not have results from testing Wi-Fi connections. This study tested sending data 10 times, and the data displayed include voltage, current, power, and usage costs. The average delay result is 1.6 seconds. A considerable time difference can occur when the Internet connected to the smart plug is unstable [31]. Sensor reading tests, including voltage,


Figure 7. Dashboard Blynk when the system is tripped

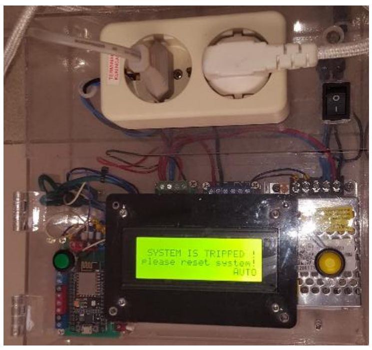



Figure 8. LCD when system is tripped

TABLE 3
EXAMINATION DELAY

| No | LCD Display Time | Blynk Display Time | Delay |
|---|---|---|---|
| 1 | 16:34:47 | 16:34:49 | 2 |
| 2 | 16:34:50 | 16:34:51 | 1 |
| 3 | 16:34:53 | 16:34:54 | 1 |
| 4 | 16:34:56 | 16:34:57 | 1 |
| 5 | 16:34:59 | 16:35:03 | 4 |
| 6 | 16:35:16 | 16:35:18 | 2 |
| 7 | 16:35:25 | 16:35:26 | 1 |
| 8 | 16:35:30 | 16:35:31 | 1 |
| 9 | 16:35:32 | 16:35:34 | 2 |
| 10 | 17:35:41 | 17:35:42 | 1 |
| Average Delay | | | 1,6 |

TABLE 4
COMPARISON OF PZEM VOLTAGE READING WITH AN AVOMETER

| Load | Voltage (V) | | Error (%) |
|---|---|---|---|
| | PZEM-004T | Avometer | |
| Hairdryer | 212,2 | 212,1 | 0,05 |
| | 218,2 | 218,2 | 0 |
| | 214,8 | 214,8 | 0 |
| | 215,1 | 215 | 0,05 |
| | 216,6 | 216,6 | 0 |
| Iron | 213,4 | 213,4 | 0 |
| | 219,3 | 219 | 0,14 |
| | 211,9 | 211,9 | 0 |
| | 211,4 | 211,2 | 0,09 |
| | 212,7 | 212,7 | 0 |
| Handphone Charger | 214,7 | 214,5 | 0,09 |
| | 218 | 218 | 0 |
| | 210,5 | 210,5 | 0 |
| | 215,5 | 215,5 | 0 |
| | 217,8 | 217,8 | 0 |
| Laptop Charger | 214,2 | 214,2 | 0 |
| | 219,4 | 219,4 | 0 |
| | 216,8 | 216,8 | 0 |
| | 215,6 | 215,5 | 0,05 |
| | 215,3 | 215,3 | 0 |
| Average | | | 0,02 |

current and power readings, were also performed by comparing the values received by the system with conventional measuring instruments, namely avometers, to determine the error value read by the PZEM-004T sensor. The avometer used is compatible with the IEC 61010 standard and has a measurement accuracy level of ±0.5% for AC voltage and ±1.0% for current [32]. This experiment was carried out by connecting each electronic device, such as a hairdryer, iron, handphone charger, and laptop charger, to the socket on the smart plug. The total test was performed 20 times by recording each value read by the sensor and avometer. The data from the current test can be seen in Table 4, the voltage test in Table 5, and the power test in Table 6.

The accuracy value when comparing the voltage value read by the PZEM-004T sensor with the avometer is in the valid category, with an error value of ±0.02%. The sensitivity of the voltage value read by the PZEM-004T sensor is valid in a calculation range of ±0% to ±0.5% [33].

The accuracy value when comparing the current value read by the PZEM-004T sensor with the avometer is in the valid category, with an error value of ±0.01%. The sensitivity of the current value read by the PZEM-004T sensor is valid in a calculation range of ±0% to ±0.5% [33].

TABLE 5
COMPARISON OF PZEM CURRENT READING WITH AN AVOMETER

| Load | Current (A) | | Error (%) |
|---|---|---|---|
| | PZEM-004T | Avometer | |
| Hairdryer | 1,723 | 1,723 | 0 |
| | 1,74 | 1,741 | 0,06 |
| | 1,743 | 1,743 | 0 |
| | 1,729 | 1,729 | 0 |
| | 1,774 | 1,774 | 0 |
| Iron | 1,499 | 1,5 | 0,07 |
| | 1,5 | 1,5 | 0 |
| | 1,503 | 1,503 | 0 |
| | 1,533 | 1,533 | 0 |
| | 1,508 | 1,508 | 0 |
| Handphone Charger | 0,063 | 0,063 | 0 |
| | 0,059 | 0,059 | 0 |
| | 0,057 | 0,057 | 0 |
| | 0,06 | 0,06 | 0 |
| | 0,059 | 0,059 | 0 |
| Laptop Charger | 0,187 | 0,187 | 0 |
| | 0,124 | 0,124 | 0 |
| | 0,102 | 0,102 | 0 |
| | 0,102 | 0,102 | 0 |
| | 0,105 | 0,105 | 0 |
| Average | | | 0,01 |

TABLE 6
COMPARISON OF PZEM POWER READING WITH AN AVOMETER

| Load | Power (W) | | Error (%) |
|---|---|---|---|
| | PZEM-004T | Avometer | |
| Hairdryer | 365,6 | 365,4 | 0,05 |
| | 379,7 | 379,9 | 0,05 |
| | 374,4 | 374,4 | 0 |
| | 371,9 | 371,7 | 0,05 |
| | 384,3 | 384,3 | 0 |
| Iron | 319,9 | 320,1 | 0,06 |
| | 329 | 328,5 | 0,15 |
| | 318,5 | 318,5 | 0 |
| | 324,1 | 323,8 | 0,09 |
| | 320,8 | 320,8 | 0 |
| Handphone Charger | 13,5 | 13,5 | 0 |
| | 12,9 | 12,9 | 0 |
| | 12 | 12 | 0 |
| | 12,9 | 12,9 | 0 |
| | 12,8 | 12,8 | 0 |
| Laptop Charger | 40,1 | 40,1 | 0 |
| | 27,2 | 27,2 | 0 |
| | 22,1 | 22,1 | 0 |
| | 22 | 21,9 | 0,5 |
| | 22,6 | 22,6 | 0 |
| Average | | | 0,1 |

The accuracy value when comparing the power value read by the PZEM-004T sensor with the avometer is in the valid category, with an error value of ±0.1%. The sensitivity of the power value read by the PZEM-004T sensor is valid in a calculation range of ±0% to ±1% [33]. In research [29] using the ZMPT101b voltage sensor and SCT-013 current sensor has an error reading value of 2.5% current measurement and 0.98% voltage measurement, while in this study from the third test of the PZEM-004T sensor readings as in Tables 4, 5, and 6, with the reading error rate is <0.5%. The resulting value is acceptable and consistent, the accuracy level is very good at the rate of 99.95% based on the calculation of the accuracy level [34].

After the accuracy value is determined by the sensor, testing is carried out on the overall power and electricity usage costs of the electronic devices installed in the house. In the research [15] only conducted tests for four devices, in this study there are 10 electronic devices tested, of the ten devices are divided into 2 categories, electronic devices that are installed continuously on the electricity of the house such as rice cooker dispenser, TV, and washing machine and devices that are used several times such as hairdryer, iron, handphone charger, laptop charger and standing lamp. The evaluation table can be observed in Table 7 with a comparison graph of the resulting power and cost values illustrated in Figure 9.

The test is carried out for 1 hour for each device. It can be seen that in Table 7 the electronic device that produces the highest power value is the hairdryer. The high power value can be caused by the value of the voltage and current flowing higher among other devices. Following Ohm's law, the power value is the multiplication of the voltage value with the current value, so that small current and voltage values can affect the power value [35]. In Figure 9, the graph of the test results carried out on all devices used at home produces a comparison graph between the power value and the generated cost which is not far apart. There is no significant difference between the value of the power and the costs incurred. Where the most expensive costs come from the hairdryer, because the highest power generated is the hairdryer device. The high value of power results in high costs on the hairdryer device, as evidenced by Equation 1 [25].

To determine the cost of using electricity from the power of electrical appliances, the determination of the electricity group used first. In research [36] conducts electrical energy monitoring by testing the system in the environment of electricity group 1 with a flow power of 900VA. Whereas in this study, the tests were carried out in group 1 of electricity with a flowing power of 1,300VA, based on the provisions that have been determined for this group given a tariff per 1kWh of 1,444.70 Rupiah. The calculation of current, power, and load has been calculated by the PZEM-004T sensor, while the calculation of costs incurred by multiplying the total kWh by the predetermined electricity tariff.

From several tests that have been performed, the system as a whole can function and perform optimally. Where the precision of the error sensor readings on the smart plug system is less than ±0.05%, namely 0.01% for the current readings, 0.02% for the voltage readings and 0.1% for the power readings. On the basis of several reference studies, it can be seen that a properly designed smart plug system can provide accurate and stable results. In addition to monitoring and control that can be done through Blynk in real-time, this system is

TABLE 7
MONITORING SYSTEM

| No | Load | Voltage (V) | Current (A) | Power (W) | Power (kWh) | Cost of use kWh @hour (Rp) |
|---|---|---|---|---|---|---|
| 1 | Rice cooker | 210,7 | 1,189 | 254,4 | 0,2585 | 373,5 |
| 2 | Fan | 210,7 | 0,3 | 39,1 | 0,0361 | 52,202 |
| 3 | Television | 217,6 | 0,283 | 34,91 | 0,0317 | 45,742 |
| 4 | Iron | 213,2 | 1,502 | 318,19 | 0,1623 | 234,517 |
| 5 | Dispenser | 223 | 0,774 | 125,82 | 0,1148 | 165,85 |
| 6 | Washing Machine | 213,5 | 1,334 | 178,25 | 0,111 | 160,336 |
| 7 | Charger Handphone | 210 | 0,061 | 7,21 | 0,0069 | 9,907 |
| 8 | Laptop charger | 212,8 | 0,259 | 28,39 | 0,0176 | 25,43 |
| 9 | Standing Lamp | 213,3 | 0,048 | 7,67 | 0,0073 | 10,563 |
| 10 | Hairdryer | 214,4 | 1,74 | 373,3 | 0,3262 | 471,307 |
| Total | | | | 1367,26 | 1,0724 | 1.549,354 |

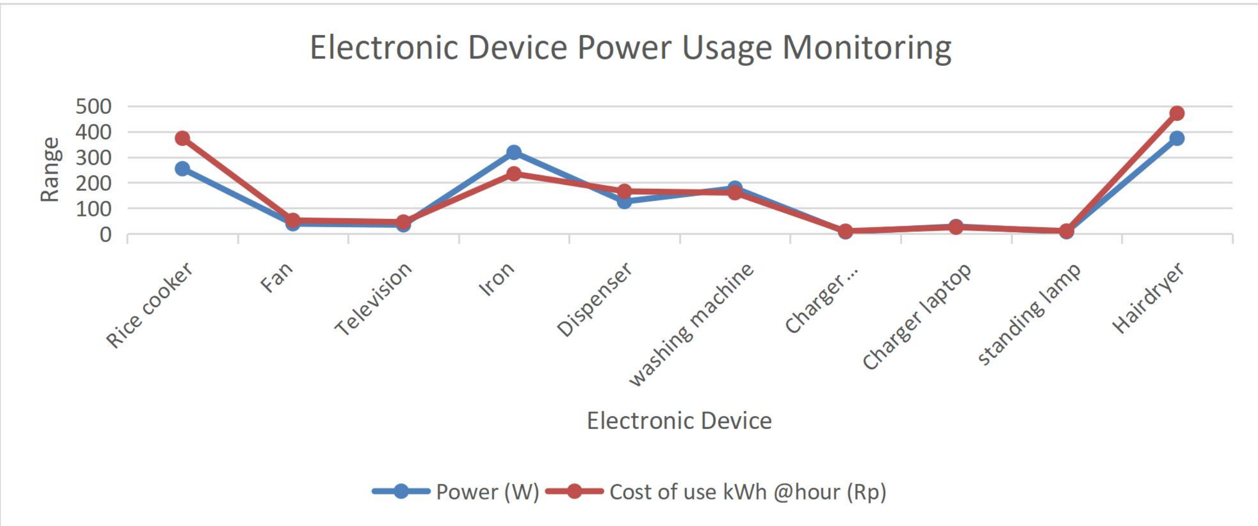



Figure 9. Monitoring system

also equipped with an overcurrent protection feature. This feature allows the smart plug to provide warning notifications and automatically cut off the electricity when the warning indicator reaches a certain limit, to prevent the risk of current surges that can cause short circuits and fires and to maintain the performance of electronic devices installed in the system because the system can provide a delay before disconnection. In addition, the system can display an indicator of the total cost of electrical energy usage with downloadable monitoring data. Not only on Blynk, the electrical measurement parameters are also displayed on the smart plug hardware in real-time.

## IV. CONCLUSION

The development of a cost-effective smart plug system with electrical energy monitoring and control features, overcurrent protection, and notification features integrated into an IoT-based plug system was successfully carried out. The designed system can measure the value of electrical parameters such as current, electricity, and power, which are displayed on the LCD and Blynk platform with a reading accuracy rate of 99.95% and can cut off the electric current when it exceeds the set limit. The development of this smart plug can be the latest technology to prevent risks such as overload and short circuits and provide awareness and user behavior of electronic devices based on real-time monitoring of power consumption, current, voltage, and cost, while also equipped with IoT-based electricity protection features. Compared to similar devices, this innovation not only improves energy efficiency and user safety but can also enable integration with the IoT ecosystem, providing smarter control and encouraging energy-efficient behavior sustainably.

## DECLARATIONS

### Conflict of Interest

The authors have declared that there are no competing interests.

### CRediT Authorship Contribution

Muntaha Hasanah: Conceptualization, Methodology, Software, Visualization, Writing-Original Draft Preparation; Dewi Indriati Hadi Putri: Data Curation, Investigation, Writing-Reviewing, and Editing; Hafiyyan Putra Pratama: Visualization, Investigation, Writing-Reviewing, and Editing.

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