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Design of Control and Monitoring System for Electrical Power on kWh Meter Based on Internet of Things (IoT)

Agus Sofwan[1], Abdullah Multi[2], Mohammad Azli[3], Nana Sujana[4]
[1]Institut Sains dan Teknologi Nasional, Jakarta, Indonesia, asofwan@istn.ac.id
[2]Institut Sains dan Teknologi Nasional, Jakarta, Indonesia, amulti@istn.ac.id
[3]Institut Sains dan Teknologi Nasional, Jakarta, Indonesia, mohammadazli76@gmail.com
[4]Politeknik Pajajaran ICB, Bandung, Indonesia, nana.sujana@poljan.ac.id

Corresponding Author: amulti@istn.ac.id[2]

Abstract: Electricity theft is the illegal use of electrical power without proper authorization and payment. This act causes losses to the electricity provider and the public, poses safety hazards, and violates the law. Perusahaan Umum Daerah (PERUMDA) Tuah Sekata of Pelalawan Regency, as a regional-owned enterprise responsible for electricity distribution to the community, annually detects indications of electricity theft through field inspections. To simplify the identification process and reduce operational costs, an Internet of Things (IoT)-based device was designed to monitor and control customers' electricity consumption.
The device utilizes a power supply as a 5V DC voltage source, a PZEM-004T sensor to measure voltage, current, power, and energy, an LCD 16x2 to display measurement results, and a 5V relay to connect or disconnect the customer's power supply. An ESP32 microcontroller processes the data and transmits it via Wi-Fi to the Blynk application, which serves as an online monitoring interface.
The device developed in this study not only facilitates real-time monitoring of electricity consumption but also serves to detect and prevent potential electricity theft. The experimental results show that, for voltage measurements, the average percentage error obtained was 0.41% (Device IoT 1), 0.29% (Device IoT 2), and 0.38% (Device IoT 3). Meanwhile, for current measurements, the average error rates were 8.42% (Device IoT 1), 8.66% (Device IoT 2), and 8.60% (Device IoT 3). Based on the experimental results, it can be concluded that the three developed IoT devices have an error rate of less than 10% (classified as very good), making them feasible for use in monitoring electrical power consumption.

Keywords: electricity theft, electricity monitoring, power control, Internet of Things (IoT), Blynk

INTRODUCTION

Electricity is one of the essential needs for humans in carrying out daily activities. Almost all modern activities depend on electronic devices that require electrical energy to function, such as rice cookers, lighting, washing machines, televisions, mobile phones, computers, and so on. Given its vital role, the utilization of electricity now covers various aspects of life, ranging from household and office needs to industrial sectors. While in the past electricity was not widely used, at present it has become a primary necessity that must be available to support daily life (Basyarudin, 2019).

In Indonesia, the management of electricity is carried out by PT PLN (Persero), a state-owned enterprise (BUMN). Therefore, individuals who wish to obtain access to electricity are required to establish a contractual sales agreement with PLN. However, the high cost of electricity has driven some individuals to commit illegal acts, such as electricity theft, in order to meet their needs. Such actions carry serious legal consequences. According to Article 362 of the Indonesian Criminal Code and Article 51, Paragraph (3) of Law No. 30 of 2009 on Electricity, anyone who uses electricity without proper authorization may be subject to imprisonment of up to seven (7) years and a fine of up to IDR 2,500,000,000 (two billion five hundred million rupiah).

The advancement of the Internet of Things (IoT) technology has created new opportunities in energy management. IoT enables devices to connect and communicate over the internet, thus facilitating remote monitoring and control. In this context, the application of IoT to kWh meters can serve as an innovative solution for monitoring and controlling electricity consumption in real time. With such a system, service providers can access energy usage information through a web-based interface or mobile application, as well as control the connected electrical devices.

Currently, most conventional kWh meters can only record energy consumption without offering real-time monitoring or remote control features. This limitation makes it difficult to identify electricity theft. Moreover, conventional systems lack flexibility in terms of integration with other technologies, such as cloud-based energy management systems or smart grids. Therefore, the development of an IoT-based kWh meter system is crucial to overcoming these limitations.

Based on the above background, this study aims to design and implement a control and monitoring system for electricity usage through an IoT-based kWh meter. The system is expected to provide a more efficient, accurate, and accessible solution for service providers, thereby enabling them to take immediate action in the event of electricity theft. Furthermore, this research is expected to contribute to the advancement of smart grid and IoT technologies in Indonesia, as well as to support efforts in energy conservation and carbon emission reduction.

METHOD

In household electrical installations, an Electricity Limiter and Meter (Alat Pembatas dan Pengukur/APP) is used to both limit the current and record the electrical energy consumed by customers in accordance with their installation contract. The APP measures the amount of electricity used, and if the power consumption exceeds the contracted limit, the electricity supply will be automatically disconnected through a Miniature Circuit Breaker (MCB). In addition to serving as a breaker for overload protection, the MCB also functions as a safety device in the event of a short circuit within the household installation.

This study proposes an Internet of Things (IoT)-based system for controlling and monitoring electrical power and energy. The system consists of a PZEM-004T current and voltage sensor module to measure electrical parameters of the load, a relay that serves as both a connector and a switch to cut off the electricity flow from PLN to the customer, and an ESP32 microcontroller module equipped with Wi-Fi capability. The ESP32 microcontroller is programmed using the Arduino IDE.

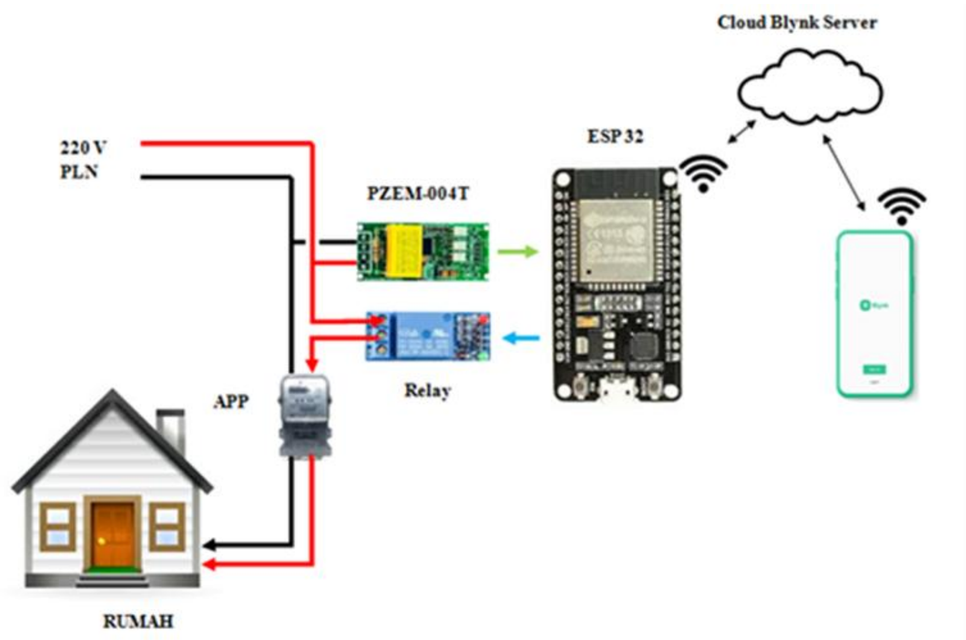


Figure 1. Schematic Illustration of the IoT-Based System

To transmit data to the cloud, a Wi-Fi connection is required. On the ESP32 module, the Wi-Fi feature is programmed to connect to the internet via a wireless network. The output data is then sent to the Blynk server, which is integrated with the cloud. The information stored on the server can be accessed through the Blynk application on smartphones (available on the Play Store) or via a PC or laptop through the official Blynk website. The design overview of the IoT-based Control and Monitoring System for electrical power on the kWh meter is illustrated in Figure 1.

RESULT AND DISCUSSION

The device is installed before the customer's Electricity Limiter and Meter (Alat Pengukur dan Pembatas/APP) provided by PLN. Its purpose is to monitor the electrical energy consumed by PLN customers. In addition, this device is designed to control the electrical load so that it does not exceed the installed capacity of the APP. If the flowing power exceeds the contracted capacity, the device will automatically disconnect the electricity supply from PLN to the customer.

The measurement results from the PZEM-004T sensor and the current transformer (CT) in terms of voltage and current can be directly displayed on an LCD screen. Furthermore, the data can also be monitored remotely through the Blynk application over the internet, and the readings can be stored in Google Sheets.

1. System Accuracy Testing

The accuracy testing of the PZEM-004T sensor and the CT was conducted to determine whether the measured voltage and current values correspond with manual measurements obtained using an AVO meter. The voltage and current values recorded by the PZEM-004T and CT sensors, displayed on a 16x2 LCD, were then compared with those obtained from manual measurements using the AVO meter.

Several steps of the accuracy test on IoT Device 1, IoT Device 2, and IoT Device 3 are as follows:

1. Prepare an AVO meter to measure the voltage and current during the testing of IoT Device 1, IoT Device 2, and IoT Device 3.
2. Prepare an electrical load using a 100-Watt lamp.

3. Connect the input of the test device to the PLN power source.
4. Attach the 100-Watt lamp load to the output of the test device.
5. Measure the PLN voltage using the AVO meter.
6. Measure the PLN current using the AVO meter.
7. Observe the LCD screen of the test device, which displays the voltage and current readings from the PZEM-004T sensor and the CT sensor.
8. Observe the AVO meter readings for PLN voltage and current.
9. Record the measurement results of voltage and current obtained using the AVO meter and compare them with the sensor readings displayed on the LCD of IoT Device 1, IoT Device 2, and IoT Device 3.

The measurement of PLN voltage using the AVO meter on the test device is shown in Figure 2.

Figure 2. Manual Measurement of Electrical Current Using an AVO Meter

In the voltage testing process, the voltage measured by the PZEM-004T sensor is displayed on the LCD screen. This voltage value is then compared with the voltage reading obtained from the AVO meter.

To determine the error percentage (%) of the PZEM-004T sensor, Equation (3.1) is applied. The calculation is performed by subtracting the voltage value measured by the PZEM-004T sensor from the voltage value measured by the AVO meter. The result of this subtraction is taken as a positive value. The obtained value is then divided by the voltage measured by the AVO meter, and the result is multiplied by 100. This produces the percentage error (%). The formula for calculating the error percentage is expressed as follows:

$$\%\ \mathbf{Error\ (Voltage)} = \frac{\mathbf{Vout\ Trafo\ PZEM\ 004T\ -\ Vout\ AVO\ meter}}{\mathbf{Vout\ AVO\ meter}}$$

As an example, the calculation of the error percentage in the first measurement is presented as follows:

Measurement - 1

Device IoT 1

$$= \frac{213.3\ -\ 214}{214} \text{ x } 100\ =\ \mathbf{0.33}\%$$

Device IoT 2

$$= \frac{213.8 - 215}{215} \text{ x } 100\ =\ \mathbf{0.56}\%$$

Device IoT 3

$$= \frac{211.8 - 213}{213} \text{x}\, 100 \;=\; \mathbf{0.56\%}$$

Table 1. Voltage Measurement Results Using an AVO Meter and PZEM-004T Sensor

Measurement Number	Data	Device IOT 1	Device IOT 2	Device IOT 3
		Voltage (Volt)	Voltage (Volt)	Voltage (Volt)
1	AVO Meter	214	215	213
	Sensor PZEM-004T	213.3	213.8	211.8
	Percentage Error (%)	***0.33%***	***0.56%***	***0.56%***
2	AVO Meter	221	218	216
	Sensor PZEM-004T	221.9	218.5	215.7
	Percentage Error (%)	***0.41%***	***0.23%***	***0.14%***
3	AVO Meter	217	213	218
	Sensor PZEM-004T	216.2	212.4	217.8
	Percentage Error (%)	***0.37%***	***0.28%***	***0.09%***
4	AVO Meter	218	216	215
	Sensor PZEM-004T	217.2	215.5	214.9
	Percentage Error (%)	***0.37%***	***0.23%***	***0.05%***
5	AVO Meter	216	215	214
	Sensor PZEM-004T	215.6	215.2	213.6
	Percentage Error (%)	***0.19%***	***0.09%***	***0.19%***
6	Multimeter	209	213	216
	Sensor PZEM-004T	209	212.5	218
	Percentage Error (%)	***0.00%***	***0.23%***	***0.93%***
7	AVO Meter	216	217	216
	Sensor PZEM-004T	214.2	216.4	215.2
	Percentage Error (%)	***0.83%***	***0.28%***	***0.37%***
8	AVO Meter	219	216	216
	Sensor PZEM-004T	217.9	215.9	215.1
	Percentage Error (%)	***0.50%***	***0.05%***	***0.42%***
9	AVO Meter	215	217	216
	Sensor PZEM-004T	213.4	215.8	214.8
	Percentage Error (%)	***0.74%***	***0.55%***	***0.56%***
10	AVO Meter	214	217	214
	Sensor PZEM-004T	213.2	216.1	213
	Percentage Error (%)	***0.37%***	***0.41%***	***0.47%***

To calculate the average error in the accuracy testing of the PZEM-004T voltage sensor, Equation (3.3) is applied. The calculation process is carried out by summing all error values (%) from each measurement and then dividing the result by the total number of measurements conducted. The formula for calculating the average error (%) is expressed as follows:

$$\text{Average \% Error} = \frac{\text{Total Error Value of PZEM} - \text{004T Sensor (\%))}}{\text{Number of Measurements}}$$

As an example, the calculation of the average error of the PZEM-004T sensor on IoT Device 1 is presented as follows.

=(0.33 + 0.41+0.37+0.37+0.19+0.00+0.83+0.50+0.74+0.37) / 10

= 0.41%

Table 2. Average Accuracy Results of the PZEM-004T Sensor

Measurement No	Device IoT 1	Device IoT 2	Device IoT 3
	Percentage Error (%)	Percentage Error (%)	Percentage Error (%)
1	0.33	0.56	0.56
2	0.41	0.23	0.14
3	0.37	0.28	0.09
4	0.37	0.23	0.05
5	0.19	0.09	0.19
6	0.00	0.23	0.93
7	0.83	0.28	0.37
8	0.50	0.05	0.42
9	0.74	0.55	0.56
10	0.37	0.41	0.47
Average	***0.41***	***0.29***	***0.38***

The purpose of calculating the error percentage is to evaluate the accuracy level of the developed IoT device. Based on Table 2, the average error (%) of the PZEM-004T sensor over 10 tests is below 10%. Specifically, the average error for IoT Device 1 is 0.41%, for IoT Device 2 is 0.29%, and for IoT Device 3 is 0.38%. Referring to Table 1, it can be concluded that the three PZEM-004T sensors used in the three IoT devices achieved an accuracy level of less than 10% (considered very good), thus making them suitable for use in this study.

2. Functional Testing of the Blynk Application

The functional testing was carried out by observing the application performance on a smartphone through the Blynk platform. The objective of this test was to verify whether the data measured by the sensors could be properly displayed in the Blynk application. The test was conducted by opening the Blynk application and monitoring the variables generated by the PZEM-004T sensor and the CT transformer. This testing was applied to IoT Device 1, IoT Device 2, and IoT Device 3. The displayed data included Voltage, Current, Power, Energy, Frequency, Power Factor, Maximum Installed Power, and Grid Status. The names and functions of each display in the application are summarized in Table 2.

Table 2. Display Names and Their Functions in the Blynk Application

Display Name	Function
Meter Number Input	Customer's meter identification number
Voltage	AC mains voltage value
Current	Current flowing to the customer
Power Consumption	Electrical power consumed by the customer
Total kWh	Total energy consumed by the customer
kWh Meter Status	Status of the customer's electrical network (ON/OFF)
Data Retrieval	Access to recorded measurement data
Maximum Power	Power setting adjusted according to the customer's installed power capacity

Several steps in the functional testing of the Blynk application on IoT Device 1, IoT Device 2, and IoT Device 3 are as follows:

1. Connect the input cables of IoT Device 1, IoT Device 2, and IoT Device 3 to the PLN power grid.
2. Connect the output cables of IoT Device 1, IoT Device 2, and IoT Device 3 to the electrical loads.
3. Activate the internet connection according to the configured SSID.
4. Open the Blynk application on the smartphone, then log in.
5. Check each monitoring display for IoT Device 1, IoT Device 2, and IoT Device 3.
6. Verify whether the displayed variables correspond to those listed in Table 2.

In this study, three IoT devices (IoT Device 1, IoT Device 2, and IoT Device 3) were tested. All three devices were integrated into a single Blynk application with three monitoring dashboards, allowing simultaneous control and monitoring of each device. An example of the functional testing result for the monitoring menu of IoT Device 1 is presented in Figure 3.

Figure 3. Monitoring Display of the Blynk Application on IoT Device 1

As shown in Figure 3, the customer's meter number can be displayed through the Blynk application. In addition, the application provides information regarding the PLN supply voltage, current, and frequency used by the customer. The electrical power and energy consumed by the customer are also displayed, allowing both instantaneous power usage and total kWh consumption to be monitored via the Blynk application. Furthermore, the grid status can be observed through the kWh meter status indicator. When the status is "ON," it indicates that the power supply is active, whereas when the status is "OFF," it signifies that the PLN power supply is disconnected.

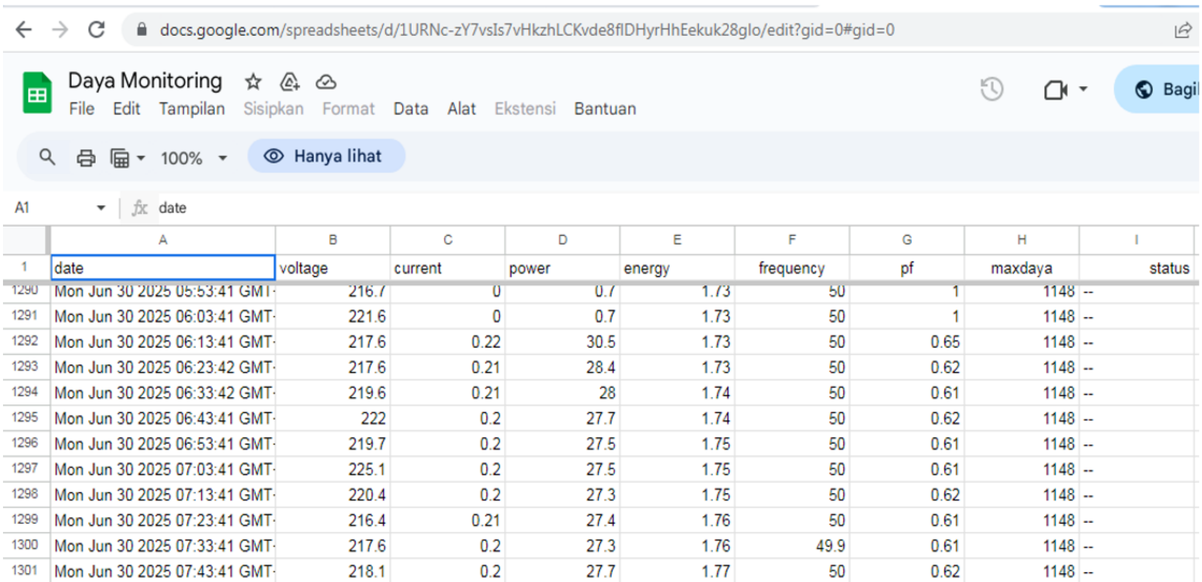
3. Functional Testing of Google Sheets

The functional testing was carried out by observing the performance of Google Sheets accessed via a smartphone. The purpose of this test was to verify whether the data measured by the sensors could be properly displayed on Google Sheets. The test was conducted by opening Google and accessing the data storage link. This functional testing was applied to IoT Device 1, IoT Device 2, and IoT Device 3. The displayed data included Voltage, Current, Power, Energy, Frequency, Power Factor, Maximum Installed Power, and Grid Status.

Several steps in the functional testing of Google Sheets on IoT Device 1, IoT Device 2, and IoT Device 3 are as follows:

1. Connect the input cables of IoT Device 1, IoT Device 2, and IoT Device 3 to the PLN power grid.
2. Connect the output cables of IoT Device 1, IoT Device 2, and IoT Device 3 to the electrical loads.
3. Activate the internet connection according to the configured SSID.
4. Open Google Sheets at the following link: https://docs.google.com/spreadsheets/d/1URNczY7vsIs7vHkzhLCKvde8flDHyrHhEekuk28glo/edit?gid=0#gid=0
5. Check each monitoring display for IoT Device 1, IoT Device 2, and IoT Device 3.
6. Verify whether the displayed variables correspond to those listed in Table 4.7.

In this study, three IoT devices (IoT Device 1, IoT Device 2, and IoT Device 3) were integrated into a single Google Sheets link with three monitoring dashboards, allowing simultaneous control and monitoring of each device. An example of the functional testing result for the monitoring menu of IoT Device 1 in Google Sheets is presented in Figure 4.



	A	B	C	D	E	F	G	H	I
1	date	voltage	current	power	energy	frequency	pf	maxdaya	status
1290	Mon Jun 30 2025 05:53:41 GMT·	216.7	0	0.7	1.73	50	1	1148	--
1291	Mon Jun 30 2025 06:03:41 GMT·	221.6	0	0.7	1.73	50	1	1148	--
1292	Mon Jun 30 2025 06:13:41 GMT·	217.6	0.22	30.5	1.73	50	0.65	1148	--
1293	Mon Jun 30 2025 06:23:42 GMT·	217.6	0.21	28.4	1.73	50	0.62	1148	--
1294	Mon Jun 30 2025 06:33:42 GMT·	219.6	0.21	28	1.74	50	0.61	1148	--
1295	Mon Jun 30 2025 06:43:41 GMT·	222	0.2	27.7	1.74	50	0.62	1148	--
1296	Mon Jun 30 2025 06:53:41 GMT·	219.7	0.2	27.5	1.75	50	0.61	1148	--
1297	Mon Jun 30 2025 07:03:41 GMT·	225.1	0.2	27.5	1.75	50	0.61	1148	--
1298	Mon Jun 30 2025 07:13:41 GMT·	220.4	0.2	27.3	1.75	50	0.62	1148	--
1299	Mon Jun 30 2025 07:23:41 GMT·	216.4	0.21	27.4	1.76	50	0.61	1148	--
1300	Mon Jun 30 2025 07:33:41 GMT·	217.6	0.2	27.3	1.76	49.9	0.61	1148	--
1301	Mon Jun 30 2025 07:43:41 GMT·	218.1	0.2	27.7	1.77	50	0.62	1148	--

Figure 4. Google Sheets Display of the Experimental Device

4. Monitoring Test of the IoT Device

This test was conducted by observing electricity usage through both the LCD display and the smartphone, which shows the sensor readings in the Blynk application. The test was carried out by connecting the device to household electrical loads as the main power distribution point. The monitoring focused on observing real-time variations in electrical parameters. The testing period was conducted from June 27 to June 29, 2025. The evaluation was performed under both load and no-load conditions, using a monitor screen as the test load, as illustrated in Figure 4.

Several steps in the functional testing of the Blynk application on IoT Device 1, IoT Device 2, and IoT Device 3 are as follows:

1. Connect the input cables of IoT Device 1, IoT Device 2, and IoT Device 3 to the PLN power grid.
2. Connect the output cables of IoT Device 1, IoT Device 2, and IoT Device 3 to the LCD monitor load.
3. Activate the internet connection according to the configured SSID.
4. Open the Blynk application on the monitoring smartphone.
5. Open Google Sheets and observe the monitored variables.
6. Verify whether the displayed variables correspond to the entries in Google Sheets.

The experimental results of IoT Device 1 over a period of three days using an LCD monitor as the load which requires 30 Watts of power based on the monitor's specification are presented in Table 3.

Table 3. Load Testing Results of IoT Device 1

Date	Time	Measurement							status
		Voltage (V)	Current (A)	Power (Watt)	Energy (Watt hour)	Frequency (Hertz)	Pf (Power Factor)	Maxdaya (Watt)	
27 Juni 2025	00.00	224.2	0	0.7	0.92	50	1	1148	--
27 Juni 2025	03.00	225.2	0	0.8	0.92	50	1	1148	--
27 Juni 2025	06.00	225.1	0	0.8	0.92	50.1	1	1148	--
27 Juni 2025	09.00	217.1	0.21*	27.7	1	50	0.61	1148	--
27 Juni 2025	12.00	220.7	0	0.7	1.05	49.9	1	1148	--
27 Juni 2025	15.00	220.5	0	0.7	1.05	50	1	1148	--
27 Juni 2025	18.00	216.8	0	0.8	1.11	50	1	1148	--
27 Juni 2025	21.00	216.6	0.2*	27.4	1.15	50	0.62	1148	--
28 Juni 2025	00.00	225.6	0	0.8	1.17	49.9	1	1148	--
28 Juni 2025	03.00	227.1	0	0.8	1.17	50	1	1148	--
28 Juni 2025	06.00	222.3	0	0.8	1.17	50	1	1148	--
28 Juni 2025	09.00	216.4	0	0.8	1.23	50	1	1148	--
28 Juni 2025	12.00	221	0	0.8	1.26	50	1	1148	--
28 Juni 2025	15.00	223.1	0	0.8	1.32	50	1	1148	--

Date	Time	Measurement							status
		Voltage (V)	Current (A)	Power (Watt)	Energy (Watt hour)	Frequency (Hertz)	Pf (Power Factor)	Maxdaya (Watt)	
28 Juni 2025	18.00	214.1	0.21*	28.3	1.33	50	0.64	1148	--
28 Juni 2025	21.00	223.6	0.19*	27	1.41	50	0.63	1148	--
29 Juni 2025	00.00	228	0	0.8	1.44	50	1	1148	--
29 Juni 2025	03.00	228.3	0	0.7	1.44	49.9	1	1148	--
29 Juni 2025	06.00	218.1	0	0.8	1.45	50	1	1148	--
29 Juni 2025	09.00	220.7	0.2*	27.5	1.54	49.9	0.63	1148	--
29 Juni 2025	12.00	220.5	0	0.8	1.55	50	1	1148	--
29 Juni 2025	15.00	220.7	0.2*	27.3	1.62	50	0.63	1148	--
29 Juni 2025	18.00	216.9	0	0.8	1.69	50	1	1148	--
29 Juni 2025	21.00	218.8	0	0.7	1.69	50	1	1148	--

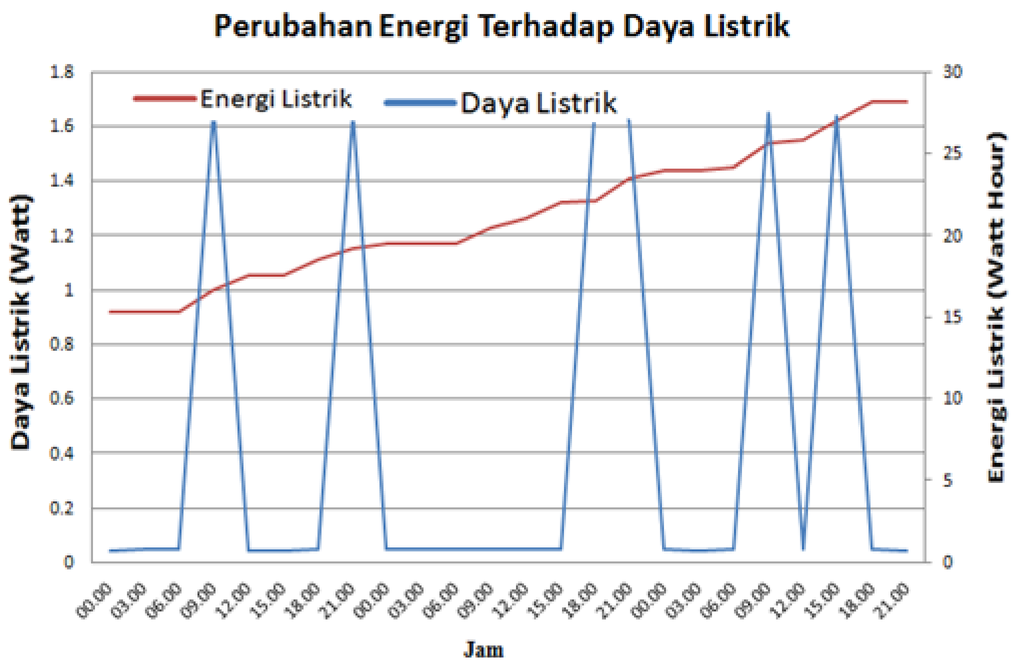


Figure 5. Load Testing Results of IoT Device 1

From Table 4 and Figure 5, it can be concluded that the variation of electrical power is always aligned with the variation of electrical energy. When IoT Device 1 is connected to a load, the recorded electrical energy increases over time according to the duration of connection. Conversely, when IoT Device 1 is not connected to a load, the amount of recorded energy remains constant without any increment. Therefore, it can be concluded that IoT Device 1 operates properly and performs its intended function.

CONCLUSION

Based on the testing, data collection, and analysis of the Control and Monitoring System of Electrical Power on the kWh Meter Based on the Internet of Things (IoT), several conclusions can be drawn as follows:

1. **Electrical Power Monitoring Capability**
   The developed IoT device is capable of monitoring the electrical power consumed by customers of PERUMDA Tuah Sekata. The system utilizes the PZEM-004T sensor and CT transformer to measure voltage and current. The measured power data are displayed directly on the LCD screen installed on the IoT device and can also be monitored online through the Blynk application via an internet connection.

2. **Electricity Theft Detection**
   The IoT device is able to identify indications of electricity theft online and in real time by comparing the measured power values with the maximum allowable power installed on the customer's kWh meter. The detection results are presented in the form of notifications in Google Sheets and the kWh meter status on the Blynk application.

3. **Electrical Power Control**
   The IoT device can control electrical power by disconnecting the PLN electricity supply when power consumption exceeds the customer's installed capacity. The voltage and current measured by the PZEM-004T sensor are processed by the ESP32, which then sends control signals to the relay. If power consumption is below the capacity, the relay remains inactive; conversely, if it exceeds the capacity, the relay is activated to cut off the electricity supply.

4. **Energy Usage Recording**
   The IoT device is able to automatically and permanently record the electrical power and energy usage of PLN customers in Google Sheets. The stored data include power, date, and time information, thereby facilitating monitoring and historical usage documentation.

5. **Percentage of Measurement Error**
   The testing results show that, for voltage measurements, the average error rates of each device are 0.41% (IoT Device 1), 0.29% (IoT Device 2), and 0.38% (IoT Device 3). For current measurements, the average error rates are 8.42% (IoT Device 1), 8.66% (IoT Device 2), and 8.60% (IoT Device 3). These findings indicate that all three developed IoT devices have error levels below 10% (considered very good), and therefore can be declared feasible for electricity consumption monitoring.

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