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Integration of a Smart Power Meter for Monitoring Household Energy Consumption in Prepaid Electrical Systems

Indah Permatasari[1*], Danny Kurnianto[2]

[1] Physics and Instrumentation Laboratory, Faculty of Telecommunications and Electrical Engineering, Institut Teknologi Telkom Purwokerto, Indonesia, 53163.
[2] Faculty of Telecommunications and Electrical Engineering, Institut Teknologi Telkom Purwokerto, Indonesia, 53163.

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Corresponding Author:

Indah Permatasari,
Email: indah@ittelkom-pwt.ac.id

ABSTRACT

Indonesian households have widely embraced the prepaid electricity payment system. The system relies on electricity credits, with each electrical device consuming credits as a unit of measurement for energy usage. A common issue is the automatic cutoff of electricity supply when the credits are depleted. This research designed a smart power meter using Current Transformer and voltage sensors. The electrical token value is then stored in the Arduino's EEPROM before being transmitted to the NodeMCU. The NodeMCU transfers the data to Antares using the MQTT protocol to forward it to the subscriber, typically an Android device. The data sent to the Android application includes current, voltage, active power, frequency, *cos φ*, and electrical credits. The measurement of electricity consumption on a kWh meter involves subtracting the value of the input electricity token from the device-measured electricity usage. The device sends a WhatsApp message when the remaining credit exceeds 10 kWh. The prototype of the smart power meter demonstrates practical functionality, with the current sensor accuracy at 99.983% and the voltage sensor accuracy at 99.999%. The largest measurement difference of the electric credit balance between the PLN Meter and the prototype is 0.04 kWh over a test period of 72 hours.

1. INTRODUCTION

Electrical energy serves diverse applications, supporting various activities and facilitating human work. The daily demand for electrical energy is rising, aligning with Indonesia's growing population (Aditio Pribadi & Syafii, 2021; Pakpahan et al., 2015). A shortage of electricity supply inconveniences domestic consumers due to the operational impact on electrical equipment, leading to economic losses for the industrial and commercial sectors (Sulaiman et al., 2007). PLN, responsible for meeting electricity needs throughout Indonesia, strives to ensure an adequate electricity supply. Based on statistical data, electricity usage is categorized into several customer segments, with industry accounting for 32.32%, households for 42.41%, the business world for 18.46%, and others—such as social, government buildings, and public street lighting—amounting to 6.81% (Sekretariat PLN, 2022).

The data results indicate that the highest supply, distribution, and electrical energy consumption are dedicated to fulfilling household activities.

Energy usage in electrical installations from PLN for each house will be recorded using a KWH meter. Two types of KWH meters are differentiated based on the payment method and electricity usage: postpaid and prepaid. In the postpaid system, electricity usage bills will be calculated monthly. Although there is no limit on electricity usage, if customers stay caught up in paying their electricity costs and fail to settle them, PLN will cut off the electricity supply (Galina et al., 2019; Hartawan et al., 2023). PLN encourages people to use electricity more wisely by switching from a postpaid system to a prepaid system. This prepaid program provides convenience for households because it saves energy more effectively and efficiently (Kurniawan & Siringoringo, 2019). The prepaid system applies electricity credit using a token number entered into the electricity meter. In principle, electricity credit or tokens will decrease along with electricity use at home, with the remaining KWH displayed on the KWH meter LCD. The presence of a prepaid electricity system makes it easy for customers to manage their electrical energy consumption (Karim et al., 2021). One of the shortcomings of this prepaid system is that consumers need to be financially prepared when their credit runs out prematurely, especially for consumers with low incomes or those experiencing economic difficulties (Akpolat et al., 2017). Another problem arises when the electricity supply is automatically cut off when the user needs help quickly topping up the electricity credit. This leads to difficulties in monitoring the remaining credit on the kWh meter due to the need for real-time tracking facilities.

There has been extensive research on prepaid electricity. The energy meter reading utilizes a GSM architecture, where, at every 30-second interval, GSM captures the latest data on units and prepaid values and sends this information to the service provider via SMS (Sultan et al., 2019). Due to the increasing development of digital technology, the Internet of Things (IoT) has found widespread applications in various fields, including health, agriculture, and smart homes(Ford et al., 2017; Rajdhev & David, 2017; Tsakiridis et al., 2020). Smart homes have been developed to monitor energy consumption with the IoT-based PZEM-004T (Irianto, 2023). Another research project created an application with automation features that allow users to disconnect the power load supply (Tahir et al., 2023). Therefore, this research aims to implement a detailed energy consumption monitoring system via an Android application. This way, users can discern patterns in electricity usage every day. Additionally, the system will be integrated with WhatsApp if the remaining electricity credit runs out, allowing users to interact to disconnect their house's electricity via WhatsApp.

2. METHOD

An alternating current (AC) is a current that flows back and forth with a certain frequency. AC voltage is a sinusoidal voltage with peak and valley values. The peak-to-peak voltage (V_{pp}) is the amount of voltage between the positive peak and negative peak on a sinusoidal wave. When measuring AC voltage, the voltage measured on the measuring instrument is the effective voltage (V_{rms}), which can be calculated using Equation (1):

$$V_{rms} = {}^{1}\!/_{2}\, x\sqrt{2}xV_{pp} \quad (1)$$

A current transformer operates based on the principle of electromagnetic induction to measure the current flowing in a cable or electrical conductor. It comprises a primary winding, a magnetic core, and a secondary winding, as depicted in Figure 1. Alternating current (AC) flowing through the primary winding generates a magnetic field in the magnetic core, thereby inducing current in the secondary winding circuit. The current in the secondary winding ($I_{secondary}$) is directly proportional to the current flowing through the primary winding ($I_{primary}$), as shown in Equation (2):

$$I_{sekunder} = CT_{truns\,ratio}\ x\ I_{primary} \quad (2)$$

where $CT_{turns\ ratio}$ is the turns ratio of the current transformer.

Electric current measurements in this study utilized the SCT013 sensor, which is a current transformer (CT) sensor. The SCT013 sensor is a device employed for measuring AC alternating current in electrical systems. The equation above expresses the relationship between the current in the primary coil and the secondary coil, influenced by the transformer turns ratio.

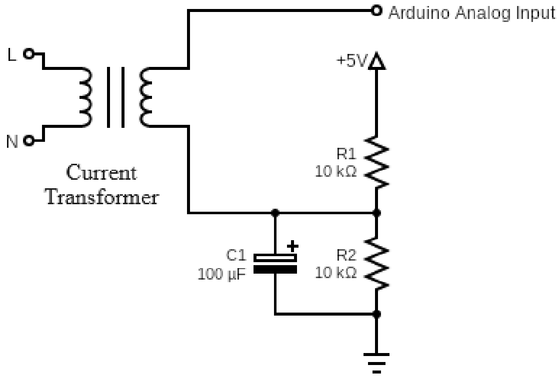


Figure 1 AC current flowing through the CT primary coil generates a magnetic field around the coil, which induces a current in the secondary coil. The junction between R1 and the CT secondary coil connects to the Arduino, allowing the microcontroller to read the current measurement signal. A 5 V power supply energizes one side of R1 while the other connects to the ground via resistor R2, forming a voltage divider.

The SCT013 sensor used has a ratio of 10A/1V, signifying that every 1 mV represents 10 mA at its output. The SCT013 sensor with a 10A/1V ratio has a maximum output of 1 V_{rms}, resulting in a maximum V_{pp} of 2.8288 V. The Arduino's ADC measurement range spans from 0 – 5 V, and since AC voltage has positive and negative peaks, a zero point at 2.5V is necessary. To achieve this 2.5V zero point, a voltage divider resistor with values R1=R2=10kΩ is required. Consequently, the maximum positive peak voltage will be 3.9144V, and the negative peak voltage will be 1.0856V. The circuit schematic for the current transformer sensor is shown in Figure 1.

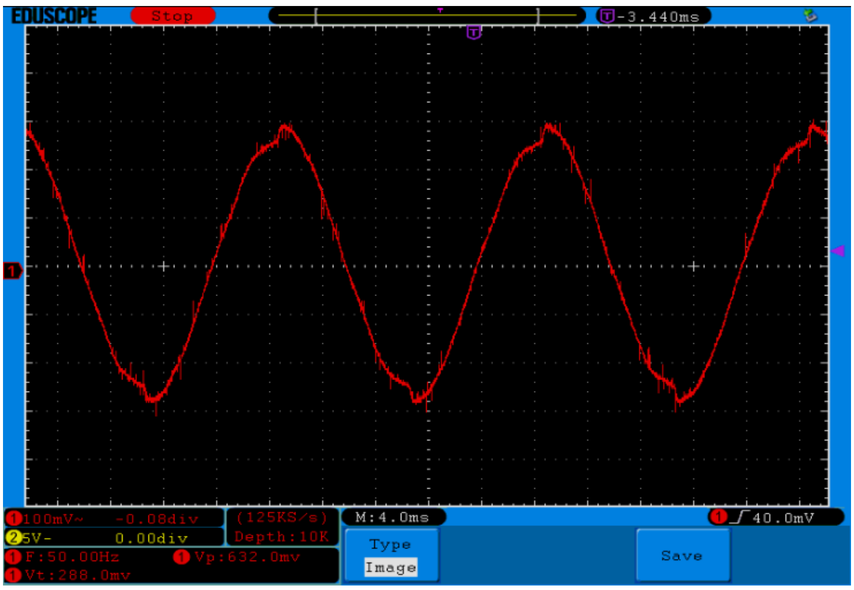


Figure 2 An oscilloscope screen displaying a peak-to-peak output voltage of 632 mV when measuring a current of 2 A using the SCT013 sensor.

An oscilloscope is used to analyze sinusoidal waveforms from the current sensor output signal, as shown in Figure 2. From these measurements, the RMS voltage (V_{rms}) of the SCT013 output can be calculated as 0.223 V. Based on the ratio of the SCT013 output voltage to the measured current at 1:10, the current measured is 2.23 A.

The research's voltage sensor used to measure a 220 V voltage employs a step-down transformer. A step-down transformer is used to decrease high voltage to low voltage. In this study, the output from the step-down transformer as the ADC input does not pass through a rectifier, as the voltage to be measured is AC voltage with a sinusoidal waveform with a frequency of 50 Hz. The schematic of the voltage sensor circuit is illustrated in Figure 3.

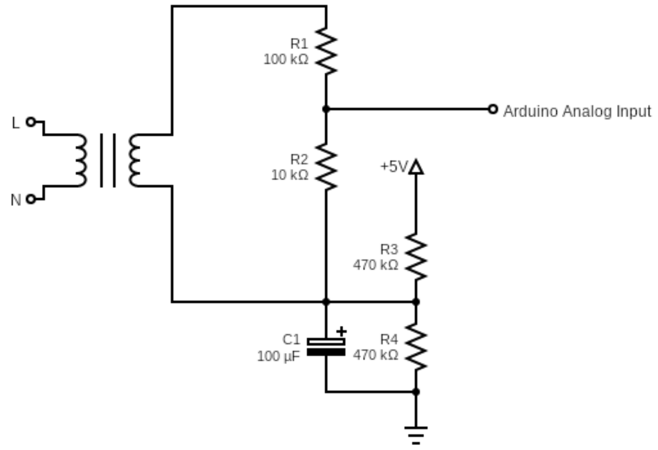


Figure 3 Voltage sensor circuit diagram.

In Figure 3, the step-down transformer has a secondary coil that generates an output voltage of 11.17 V_{rms}. The step-down transformer's peak-to-peak voltage is 31.6 V, which means it has a positive peak voltage of 15.8V and a negative peak voltage of -15.8V. To adapt this voltage as an Arduino analog input (Analog to Digital Converter), where the working voltage is 0 - 5 V, it is necessary to reduce the output voltage. A voltage divider resistor is employed for this purpose, consisting of R1 with a value of 100 kΩ and R2 with 10 kΩ. This configuration is designed to achieve the desired peak-to-peak output voltage of 2.87 V.

Similarly, when measuring electric current using the SCT013, measuring AC voltage, which is a sinusoidal waveform, requires a zero-point measurement at a voltage of 2.5 V to ensure that the positive peak voltage and negative peak voltage remain within the range of 0 – 5 V, namely 3.935 V for the positive peak and 1.065 V for the negative peak. To establish the 2.5V zero point, a voltage divider resistor of R1=R2=470kΩ is used, as depicted in Figure 3.

Figure 4 displays the Channel 1 oscilloscope output with a scale of 5 V/div, illustrating the peak-to-peak voltage from the step-down transformer output, measuring 30.2 V. Simultaneously, the Channel 2 display, with a scale of 1 V/div, presents the voltage from the output of the voltage divider circuit, registering at 2.72 V. Given the peak-to-peak voltage of 2.72 V, the output from the voltage divider circuit is suitable for use as an Arduino analog input.

Electric power is the rate of delivering electrical energy produced in a system or device within a specific period. Power units are expressed in watts, indicating the level of electrical energy consumption. Electrical power is categorized into three types: Active, Reactive, and Apparent. Active power, also known as real power, is a component of the total power that encompasses the power effectively utilized. It is obtained through the product of voltage (V), current (I), and the power factor coefficient ($\cos \phi$), as expressed in Equation (3):

$$P = V \ x \ I \cos \Phi \qquad (3)$$

Based on Equation (3), the cosine of the phase angle (ϕ) between voltage (V) and current (I) indicates the time difference between the voltage and current waves in the AC system.

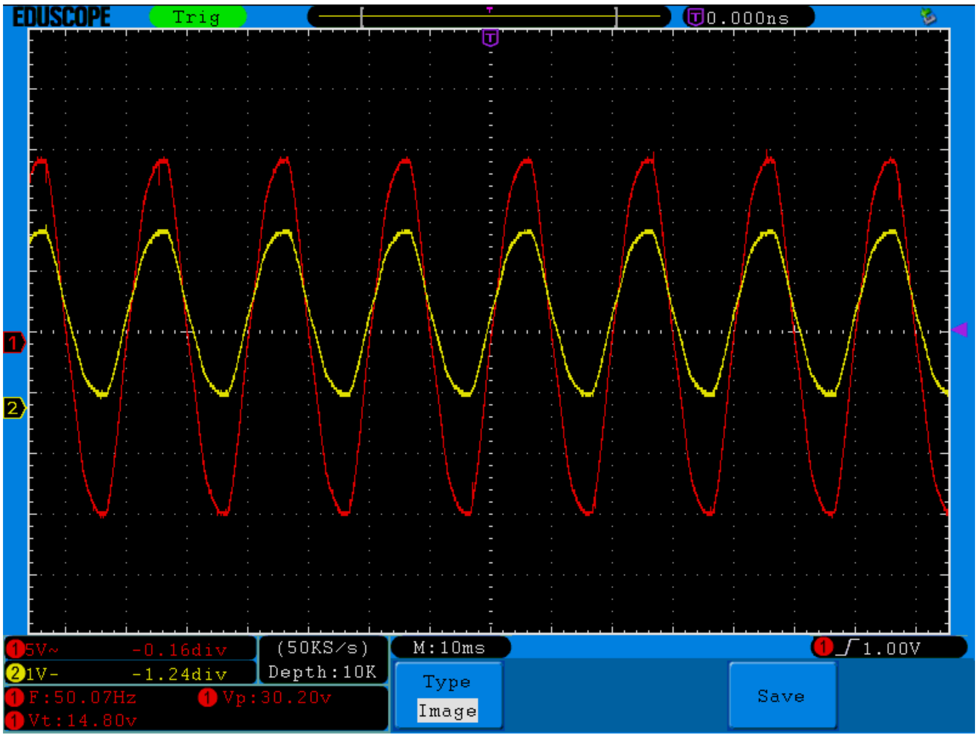


Figure 4 The peak-to-peak (V_{pp}) measurement results for transformers and voltage dividers.

Reactive power (*Q*) is the total electrical power required to generate a magnetic field in the inductive load coil. It is measured in Volt-Ampere Reactive (VAR) units and plays a crucial role in maintaining voltage and current stability in an electric power system. The mathematical equation for calculating reactive power is as follows:

$$Q = V\ x\ I\ sin\ sin\ \Phi \tag{4}$$

Apparent power (*S*) is the total power flowing into an alternating current (AC) circuit. It is obtained by multiplying voltage (*V*) and current (*I*), disregarding the phase angle difference between the two. To calculate the apparent power in an AC circuit, the formula is as follows:

$$S = V.I \tag{5}$$

The relationship between active power (*P*), apparent power (*S*), and power factor ($cos\ \phi$) is shown in the mathematical equation below:

$$S = \frac{P}{cos\ cos\ \varphi} \tag{6}$$

Power factor is the ratio of active power to apparent power. It serves as a crucial indicator for assessing the effectiveness of a load in carrying out its function with respect to power dissipation. Higher power efficiency is achieved when the real power (*P*) is approximately equal to the apparent power (*S*), resulting in a phase angle cosine value ($cos\ \phi$) close to or equal to 1. A low power factor can have adverse effects, leading to high load currents. It is worth noting that most loads in electrical systems are inductive (Rustemli & Ates, 2012).

The block diagram for research on a smart power meter designed to monitor household-scale energy consumption is shown in Figure 5. Simultaneously, the AC-to-AC adapter is employed to measure voltage, facilitating the calculation of apparent power, real power, and power factor. To determine electricity consumption in kilowatt-hours (kWh), one subtracts the value of the electricity token. Subsequently, this value is stored in the Arduino EEPROM and then transmitted to the

NodeMCU. The NodeMCU functions as a bridge between the prototype and Antares as an IoT platform. It is a device equipped with WiFi connectivity features that connect to a WiFi network for communication with Antares. When data is received from Arduino, NodeMCU sends this data to Antares using the Message Queue Telemetry Transport (MQTT) protocol, allowing access to measurement data via an Android device. Similarly, when the Android device sends device setting data to Antares, NodeMCU forwards this data to Arduino, and NodeMCU stores the data in EEPROM as a backup. One online data collection medium that can be utilized is the Antares storage platform (Devi et al., 2019; Saputra et al., 2019).

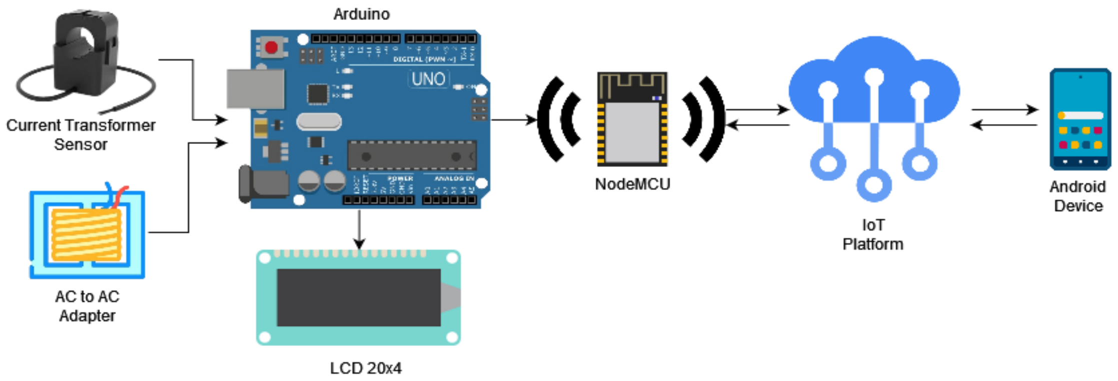


Figure 5 Power meter block diagram.

The IoT protocol utilized in this research is the MQTT protocol. MQTT is a lightweight messaging protocol suitable for machine-to-machine (M2M) communication, distinguished by its smaller packet header compared to other protocols like HTTP and CoAP (Foster, 2015; Naik, 2017; Outeirino & Garcia, 2017). In this study, the Antares platform serves as a broker in the MQTT protocol, facilitating the forwarding of topics (measurement data) from the publisher (prototype) to the subscriber (Android device). Additionally, the MQTT protocol was employed in this research to both retrieve and set the kWh value set point via an Android device.

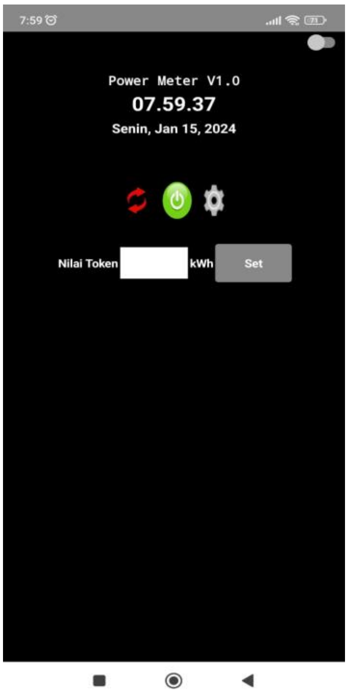


Figure 6 Set point kWh in the android application.

Two types of data are sent to Antares: real-time and measurement data at 30-minute intervals. Real-time measurement data is sent directly by the prototype at any given moment. In contrast, interval measurement data represents information from the last measurement taken at the 30th minute of every hour. This allows for a comparison with kWh meters at the same time. In this research, the prototype is designed to measure current, voltage, and electrical power and calculate household electrical power usage. The calculation involves setting the initial value (set point) of the kWh value on the prototype equal to the PLN kWh meter. Subsequently, this value is subtracted from the kWh value obtained from the prototype measurement.

Figure 6 illustrates the kWh set point menu of the Android application. This study utilized an Android application, functioning as a user interface, for manually configuring the kWh value set point. The PLN kWh meter value is inputted into the application and submitted, and the kWh value is subsequently transmitted to the prototype for storage in EEPROM. This procedure is referred to as the kWh value setpoint entry. In the event of a power loss to the prototype, this ensures the retention of the kWh value, preventing its deletion. The set point referred to in this study is the electricity credit balance displayed on the PLN kWh meter screen before measurement. Due to limitations in this study, automatic reading of the electricity credit value displayed on the PLN kWh meter is not yet possible, thus requiring manual input. The set point entry is intended to align the initial electricity credit value between the PLN kWh meter and the prototype so that the measurement accuracy of the prototype can be compared.

3. RESULTS AND DISCUSSION

3.1 Prototype Configuration

Testing the smart power meter prototype includes electric current measurement testing, household voltage measurement testing, and prototype integration testing in household installations. Electric current and voltage measurement tests are conducted by comparing measurements obtained using standard measuring instruments with those obtained using the prototype. The purpose of the integration test is to compare the kWh measurements made by the prototype with those from the PLN kWh meter.

(a) (b)

Figure 7 Prototype of (a) internal section and (b) external section.

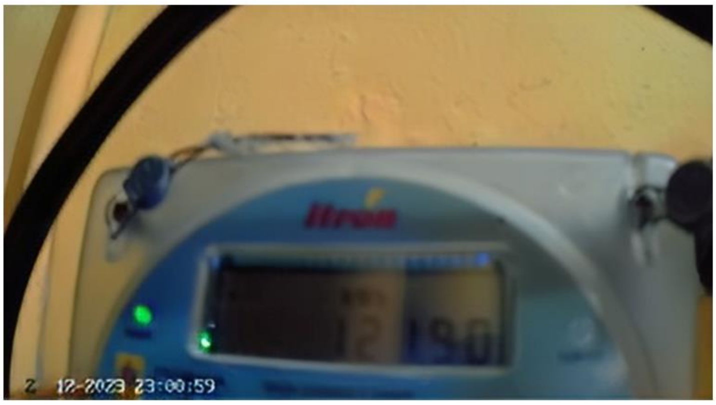
Figures 7(a) and 7(b) illustrate the internal and external sections of the smart power meter prototype. Figure 7a shows the components of the prototype, including a step-down transformer used as a voltage sensor, an SCT013 current sensor, an Arduino, and an ESP8266 module. Figure 7(b) presents the measurement results displayed on the LCD, which include voltage, electric current, power usage, power factor, electricity balance in kWh units, and the measured consumption of electric power in kWh.

Table 1 Comparison before and after SCT013 sensor calibration.

Load	Clamp Meter	SCT013 Sensor Uncalibrated	SCT013 Sensor Calibrated
Load 1	0.16	0.18	0.17
Load 2	0.17	0.19	0.18
Load 3	0.19	0.21	0.2
Load 4	1.87	1.94	1.86
Load 5	0.47	0.54	0.49
Load 6	1.35	1.4	1.35
Load 7	2.17	2.25	2.16

Before testing electric current measurements with the SCT013 sensor, calibration is essential to enhance measurement accuracy. Calibration involves measuring the electric current with various loads to derive a multiplier factor, ensuring that the SCT013 sensor measurements align closely with those obtained using a clamp meter. This process involves measuring currents ranging from below 0.1 A to 2 A, then dividing the prototype measurement results by the clamp meter readings to obtain a constant, which in this case is 0.96. The SCT013 sensor has a voltage-to-current ratio of 1:10, where every 1 mV of output voltage represents 10 mA of measured current. The calibration constant of 0.96 is multiplied by 10, resulting in a new ratio where 1 mV represents 9.6 mA. The floating point in the calibration process is adjusted to match the floating point of the clamp meter, with two digits after the decimal point. The results of electric current measurements using the SCT013 sensor before and after calibration was shown in Table 1.

(a)



(b)

Figure 8 Monitoring results of (a) prototype via android application and (b) PLN Meter via CCTV.

Different loads and prototypes were used in electric current measurement experiments to obtain a range of current values. Random household voltage measurements were then conducted to obtain a range of voltage values. The findings from thirty tests carried out to measure voltage and current in homes are presented in Table 2.

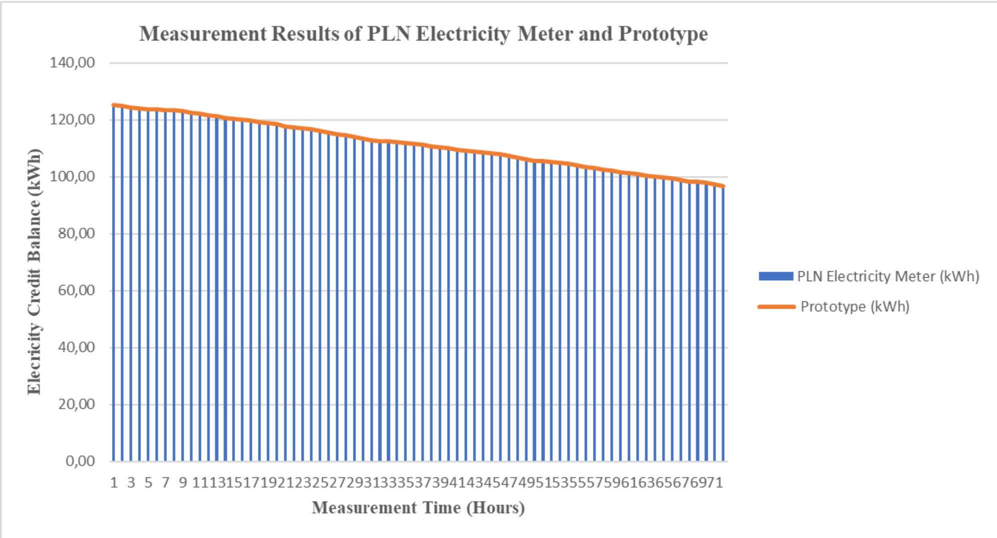
Table 2 Calibration results for current and voltage sensors.

No	Current (Ampere)		Voltage (Volt)	
	Prototype	Multimeter	Prototype	Multimeter
1	1.02	0.992	230	230
2	1.43	1.403	230	230
3	0.95	0.945	231	230
4	0.95	0.945	230	229
5	1.43	1.399	228	228
6	0.95	0.943	230	230
7	1.98	1.948	229	229
8	1.06	1.045	229	229
9	1.52	1.502	228	228
10	1.06	1.043	229	229
11	2.08	2.03	227	227
12	3.44	3.34	226	226
13	2.82	2.805	228	228
14	2.3	2.267	228	228
15	2.3	2.27	229	229
16	2.3	2.243	228	228
17	2.17	2.111	226	226
18	1.67	1.63	227	227
19	1.79	1.741	227	228
20	1.79	1.761	229	229
21	2.01	1.978	228	228
22	0.71	0.711	228	228
23	0.72	0.716	228	228
24	0.58	0.58	229	229
25	0.58	0.577	230	231
26	1.26	1.233	231	231
27	1.25	1.241	231	231
28	4.8	4.67	231	231
29	3.09	2.998	231	231
30	5.3	5.143	231	231

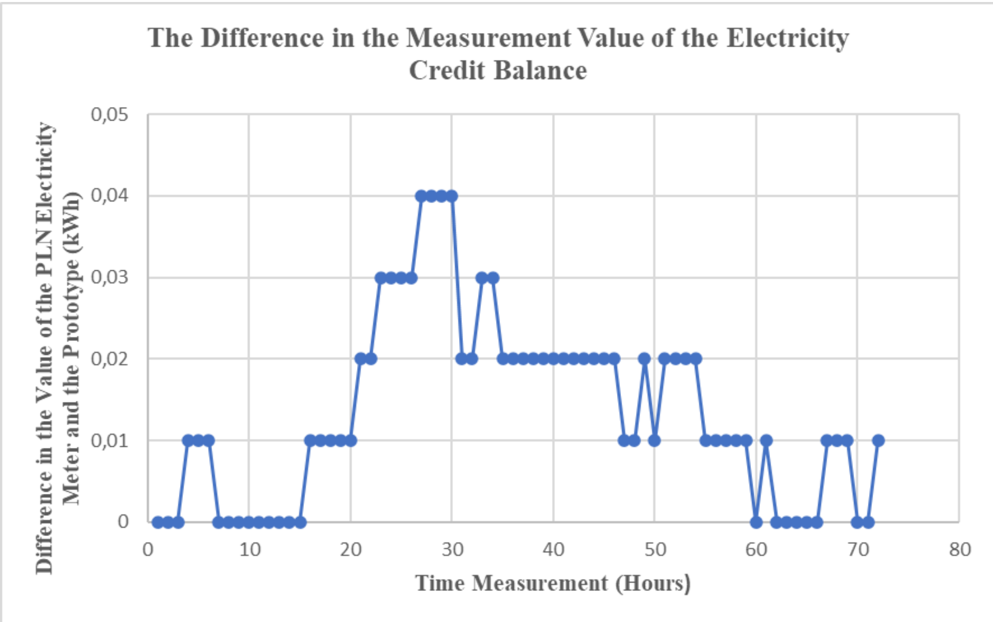
Based on the data in Table 2, the current sensor exhibits an accuracy of 99.983% with an error of 0.017%. Meanwhile, the voltage sensor demonstrates an accuracy of 99.999% with an error difference of 0.001%. These results indicate a minimal error rate, suggesting that the created prototype can closely approximate actual values.

3.2 Monitoring and Communication

Figure 8 illustrates the smart power meter application. It shows that the remaining electrical credits on the prototype and PLN meter both register a value of 121.90 kWh. The communication system between devices and user interfaces utilizes the MQTT protocol, facilitating real-time data exchange. The application presents crucial parameters such as voltage, current, electrical power consumption, frequency, and power factor (*cos φ*). As depicted in the results, a *cos φ* value of 0.97 indicates a very high power factor, closely approaching the optimal value of 1. With a value of 0.97, it can be inferred that nearly all the supplied power to the circuit is utilized for useful work (active power), with only a small portion dedicated to reactive power. Consequently, the household demonstrates high energy efficiency due to its elevated power factor. Additionally, the measured frequency stands at 50.13 Hz, a significant parameter, as changes in frequency can signify instability in the electrical system, potentially causing damage to electronic equipment. The smart power meter application furnishes detailed information, facilitating user-friendly monitoring and control of electricity consumption at home.



(a)



(b)

Figure 9 (a) Monitoring measurements of electric credit balances and (b) difference in kWh values between PLN meter measurements and the prototype.

Figure 9(a) demonstrates that measuring the electricity credit balance from the prototype yields values closely aligned with the PLN kWh meter. The monitoring is conducted continuously for 72 hours, with data recorded every hour. The initial electricity credit balance before usage is 125.3 kWh. The consumption of electrical energy resulted in reduced electricity credit, with the prototype showing an electricity balance of 96.76 kWh after 72 hours of use, while the PLN kWh meter indicated an electricity credit balance of 96.75 kWh. Figure 9(b) shows that during real-time measurements, the highest difference in electrical credits between the prototype and the PLN kWh meter was 0.04 kWh, and the lowest was 0.01 kWh for each data recording at 1-hour intervals. Consequently, the implemented tool for measuring household electrical energy consumption works effectively and accurately..

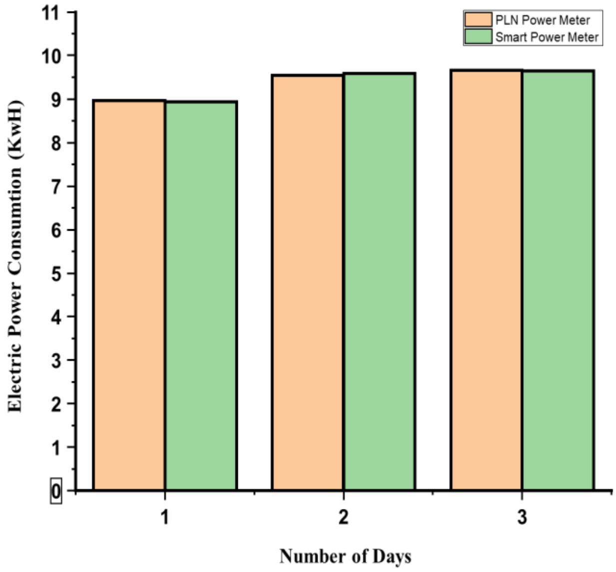


Figure 10 Electricity consumption per day.

Figure 10 shows the monitoring results of power consumption measurements implemented at home over three days. On the first day, electrical power consumption was 8.96 kWh for the PLN kWh meter and 8.93 kWh for the prototype. On the second day, electricity consumption was 9.55 kWh on the PLN meter and 9.59 kWh on the prototype. On the third day, electric power consumption was 9.64 kWh on the prototype and 9.67 kWh on the PLN Meter. A noteworthy feature of this prototype is its ability to send messages via WhatsApp as a warning system when the electricity credit balance falls below 10 kWh or if the electricity balance is depleted.

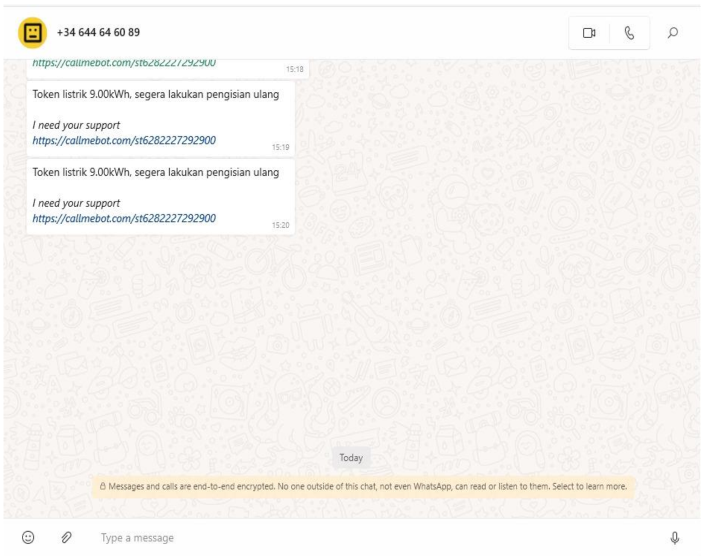


Figure 11 Electricity credit balance alart message via Whatsapp.

Figure 11 displays a notification message indicating that the remaining balance of electricity credit is 9 kWh. The warning about the remaining electricity balance sent via WhatsApp addresses the fact that the circuit on the PLN kWh meter will automatically cut off the electricity supply to prepaid electricity customers when the electricity credit balance is depleted. This system effectively solves issues when the user is not at home.

4. CONCLUSION

Based on the prototype testing results in this research, measuring electric current using the SCT013 sensor demonstrates good accuracy, which is further enhanced through calibration. The proper selection and calibration of the SCT013 sensor ensure precise measurement results. Additionally, the use of a step-down transformer as a voltage sensor highlights the importance of adhering to transformer specifications to achieve optimal measurement accuracy.The accurate measurement of electric current and voltage is crucial for precisely calculating electric power consumption, as both parameters directly influence the amount of power consumed. The power factor ($cos\ \varphi$), influenced by household electrical devices, plays a pivotal role in assessing power efficiency. Moreover, the implementation of the MQTT protocol for communication between devices and user interfaces proves highly efficient. This protocol facilitates seamless data exchange, enabling real-time monitoring and control of electricity consumption at home. Overall, the findings underscore the effectiveness of the smart power meter prototype in accurately measuring and monitoring electrical parameters, thereby enhancing energy management and efficiency in household settings..

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