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Design and Performance of a Solar-Powered Single-Phase Smart Energy Monitoring System

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***Abstract* - Energy management involves the systematic monitoring, optimization, and control of an organization's energy consumption to conserve energy and reduce associated costs. While conventional smart meters have some adaptive capabilities, ensuring continuous operation during outages and maintaining energy efficiency pose challenges for their power supply. This study focuses on the design and installation of a solar-powered, single-phase smart energy monitoring system. The objectives are to assess its real-time monitoring performance against a utility meter and evaluate its photovoltaic system. The design incorporates a 1000:1 split-core current transformer and the PZEM-004T, with power primarily supplied by a 15W monocrystalline solar panel and augmented by a 12V 7Ah lead-acid battery. Energy monitoring is further integrated with standardized electrical considerations to ensure safety. Results show acceptable percent errors within standard registration, with notably improved performance under higher loads. Specifically, the system demonstrates an average power error of 0.80% at 500W and 0.40% at 1500W in a residential setting and exhibits a 1.07% month-long accumulated energy error compared to a CA0.5 meter. Using the designed photovoltaic supply, the system can generate seven times more energy than it consumes and operate independently for up to 84 hours on battery power alone. Additionally, the monitoring system identifies voltage fluctuations in the dwelling. Further examinations could explore its potential for monitoring three-phase systems and industrial applications with higher loads.**

***Keywords:* Voltage, Split-Core CT, Pzem-004t, Monocrystalline, Lead-Acid**

I. INTRODUCTION

Energy management entails the methodical and forward-looking surveillance, regulation, and enhancement of an organization's energy usage, aiming to conserve energy and minimize related expenses. It encompasses actions such as monitoring monthly energy bills and switching to energy-efficient light bulbs. Global primary energy consumption has significantly risen over the past few decades, leading to increased flexibility in residential usage and more pronounced fluctuations in load [1]. Consequently, between 2000 and 2015, residential electricity consumption in the Philippines saw a substantial increase, with total consumption rising from 12.7 terawatt-hours in 2000 to 22.7 terawatt-hours in 2015, equating to an annual per capita growth rate of about 2.0% [2]. Another important factor to consider is the power factor, defined as the ratio of true power in watts (P) to apparent power in volt-amperes (S). As noted by Kumar [3], power factors are typically considered poor if they are 0.85 or less. When household electrical loads have low power factors, the amount of power needed to complete a task increases significantly, leading to higher energy usage and increased costs for installations or equipment.

In a consumer setting, electric appliances can be categorized into three types: resistive, inductive, and capacitive loads. According to Ponniran *et al.,* [4], resistive loads, which usually consist of heating elements, require high power, making their power factor equal to 1. In contrast, loads containing inductive (electric motors) or capacitive elements are classified as reactive loads. Such appliances consume less power and have a lower power factor compared to heating element loads.

The smart grid (SG) represents a shift towards a more interactive, decentralized, and adaptable role for end-users in the daily operation of the infrastructure. As a result, there has been increasing interest in home energy management systems (HEMS) and smart monitoring over the past few years [5]. Smart energy meters (SEMs) are electrical devices equipped with an energy meter chip to measure consumed electric energy, complemented by a wireless protocol for data communication. SEMs provide comprehensive consumption data, serving the dual purpose of reducing electricity bills and enhancing knowledge about the electricity grid's status [6]. Numerous researchers have explored HEMS and smart energy monitoring using microcontroller chips such as ESP32 and Arduino [7, 8], achieving positive outcomes. However, related studies often lack innovation in power supply. Most SEMs rely on the grid as their power source. Designers of power supplies for smart meters face various challenges, addressing not only common considerations like energy efficiency but also ensuring proper functionality during electrical power failures [9]. The introduction of reliable battery and solar technology into smart energy monitoring holds significant promise for enhancing continuous operations.

Unlike traditional meters, smart energy meters offer several advantages. Smart electricity meters replace conventional meters to increase measurement accuracy, efficiency, features, privacy, security, and visibility of specific locations. Moreover, smart meters allow customers to access electricity consumption patterns of individual household appliances [10]. Traditional kilowatt-hour meter readings and outdated meter technology lack real-time and accessible data capabilities, posing challenges for consumers and end-users in monitoring their energy consumption. Additionally, traditional meters are susceptible to human errors, leading to billing discrepancies [11]. The absence of an effective monitoring system can leave consumers unaware of their current energy consumption patterns, making efficient energy management difficult. In contrast to most studies on smart monitoring systems [12, 13], where real-time to historical monitoring of augmented power parameters and electrical safety considerations are often absent, this study emphasizes accessible real power, power factor, and estimated kWh bill monitoring, while ensuring reliable electrical protection and a stand-alone power source through the implementation of solar technology. Primarily, this research project aims to develop and install a solar-powered single-phase smart energy monitoring system with integrated features for real-time voltage, current, and power tracking. This system relies primarily on solar technology as its main power source.

Specifically, the objectives are to:

1. Measure the monitoring system's real-time power and energy (kWh) reading performance in comparison to a utility energy meter.
2. Evaluate the performance of the photovoltaic setup in supporting the smart monitoring system.
3. Use the smart energy monitoring system to observe the residential dwelling's voltage fluctuations over the course of a day.

II. MATERIALS AND METHODS

This study employs an experimental research approach, a technique for gathering information and data on a subject through observation in controlled settings. This method aligns with the assessment of real-world applicability and precision in the context of energy monitoring.

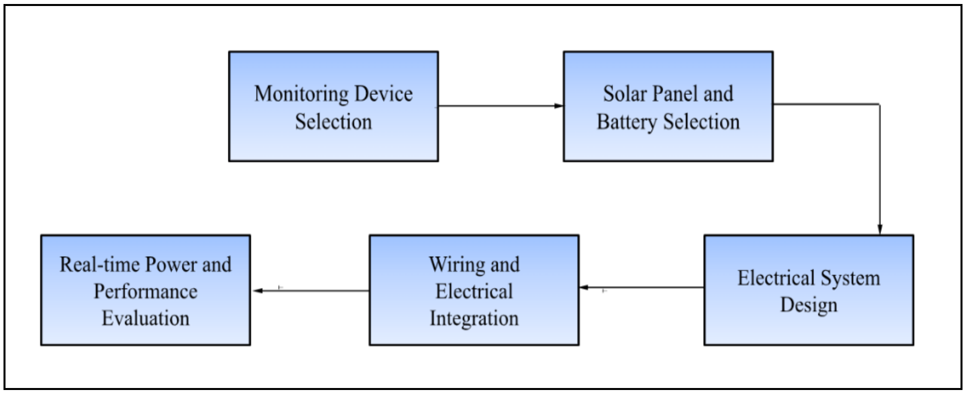

Fig. 1 Methodological framework

A. Study's Electric Cooperative

This study will utilize the electricity characteristics and retail rates from the Pampanga II Electric Cooperative (PELCO II) in Pampanga, Philippines. PELCO II oversees the operations, service, and maintenance of electricity distribution in seven municipalities, including Mabalacat City, Lubao, Guagua, Sta. Rita, Porac, Bacolor, and Sasmuan. The region adheres to a standardized nominal voltage of 230 V and a frequency of 60 Hz, using a line-to-neutral circuit configuration [14].

B. Current Transformer

A 100 A split-core current transformer, featuring a single primary winding and a corresponding secondary winding with a ratio of 1000:1, was used. This CT ratio was chosen to meet the precise needs of the measuring module, where the allowable current threshold of the AC communication module should not exceed 100 A [15]. This choice is in accordance with the IEC 60044-8: Instrument Transformers (2002) standard. The current transformer will be directly connected to the AC communication module using a 0.3 mm² or 22 AWG silicone wire cable and will serve as the primary means for detecting the system's current. Although the standard length for split-core current transformers is 2.4 meters, according to the National Electrical Code (NEC), lead wires can be extended up to 30 meters if extension wires of standardized #18 to #22 AWG are enclosed within a conduit.

C. Monitoring Component Selection

The project's assembly is designed to accommodate residential to small-scale commercial settings, with a maximum total connected load of 100 A. The PZEM-004T V3.0 AC communication module will be employed as the primary component for capturing and monitoring the electrical parameters of the system. This module, along with a built-in voltage divider circuit and the installed external current transformer, is responsible for measuring and reporting electrical parameters including power, current, voltage, energy consumption, and power factor, with a current reading threshold of 100 A. The PZEM-004T AC communication module is a well-established component for energy monitoring and has been a key part of numerous research studies in electrical engineering [16, 17].

Given the proliferation of Wi-Fi hotspots and their adequate range for the required monitoring, the prototype employs Wi-Fi as the chosen mode of communication. The devices are managed within the Blynk application, implemented using the ESP8266. As noted by Durani [18], Blynk is an online platform that facilitates the control and monitoring of electronic devices through iOS and Android, offering a customizable dashboard, sensor data storage, and compatibility with various hardware platforms, including Arduino and ESP8266. Many studies and research have explored and integrated smart monitoring with the Blynk platform, establishing its reputation as a reliable interface for the project [19, 20].

To facilitate power calculations and communication through the Blynk interface, the ESP8266 was utilized as the system's microcontroller, connected to the PZEM-004T (RX, TX) through software pins 14 and 12. According to Gopika [21], unlike the Arduino, which lacks built-in support for wireless networks, the ESP8266 or NodeMCU is a microcontroller with integrated Wi-Fi connectivity and microcontroller capabilities that can be powered through a 5V DC supply. Programming the NodeMCU is possible through the Arduino IDE, using the C++ programming language, enabling it to perform and communicate the necessary augmented power calculations, initially derived from the theory [22].

$$Power\ Factor = \frac{Real\ Power\ (P)}{Apparent\ Power\ (S)} = \cos\ (phase\ angle) \quad (1)$$

If the voltage, current, and angle are readily detected, the real power (P) parameter can be calculated using the cosine function [23]:

$$Real\ Power\ (P) = V\ x\ I\ x\ \cos\ (phase\ angle) \quad (2)$$

The combination of these formulas is often referred to as the "power triangle." To determine the estimated kWh bill, the total energy consumption (kWh), or the unit of electricity listed on electricity bills, should first be calculated:

$$Energy\ (kWh) = \frac{Real\ Power\ (W) x\ Time\ (hrs)}{1000} \quad (3)$$

The proposed smart energy monitoring system will utilize a 20x4 LCD display screen with an I2C communication interface. The standard module dimensions are 98mm x 60mm, with a viewing area of 77mm x 25mm.

D. Solar Panel and Battery Selection

For the system to function continuously, the monitoring component requires a stable and reliable power source. A photovoltaic and battery setup has been designated as the system's primary power source, ensuring continuous operation and addressing issues related to power disruptions. In the current era of rapid growth in renewable energy applications, managing community electricity demand while ensuring 24/7 energy security is a challenging issue. Therefore, a renewable energy source is essential for long-term sustainability [24]. The system is primarily powered by a 15 W monocrystalline solar setup with 10 A PWM (Pulse Width Modulation) technology, complemented by a 7 Ah, 12 V battery, as calculated using equations (5) and (6). The monitoring component operates at a voltage rating of 5 V and a current rating of 0.1 A, functioning 24 hours a day.

$$Daily\ Consumption\ (Wh) = \sum Qty\ x\ power\ (W)\ x\ hours\ (h) \quad (4)$$

This results in an energy requirement of 2.4 ampere-hours (Ah) and a daily wattage consumption of 12 watt-hours (Wh). Based on a total consumption of 12 Wh per day, the determination of battery capacity for a 3-day span of autonomy is outlined in [25]:

$$Battery\ (Ah) = \frac{(Total\ Wh\ per\ day) x\ (Days\ of\ Autonomy)}{efficiency\ x\ DOD\ \ x\ Nominal\ Voltage} \quad (5)$$

In this context, the battery efficiency is set at 0.85, with a projected depth of discharge (DOD) estimated at 0.5 for lead-acid batteries. The battery specification is determined to be 12 V, 7 Ah lead-acid. The minimum size of the solar panel, under ideal conditions, was calculated to provide sufficient capacity to effectively harness energy during a 1-hour duration of sunlight and charge the battery, using [25]:

$$Solar\ Size\ (W) = \frac{(Total\ Wh\ per\ day) x\ (System\ Losses)}{Sun\ hours\ (hrs)} \quad (6)$$

The total daily consumption of the monitoring component is 12 Wh, while system losses are estimated to be 0.8 [25]. Given the solar panel's ideal 15 W, 1.25 A monocrystalline specification and the battery's 12V rating, a 12 V, 10 A PWM solar charge controller was selected. The system will use the 5 V, 3 A micro-USB port on the solar charge controller as the main power supply connection to the monitoring component. The solar setup will include a 6AT DC circuit breaker connecting the panel to the solar charge controller. The DC system will utilize 1.024 mm^2 or #18 THHN wire, in accordance with NEC 310-16 standards [26]. The circuit breaker ampacity for the solar panel was determined with reference to [27]:

$$Total\ Current\ (I) = \frac{Peak\ Power\ (Pmax) x\ 125\%}{System\ Voltage\ (V)} \quad (7)$$

E. System Design

The system assembly of the proposed solar-powered smart energy meter aligns with the predetermined components, ensuring adherence to electrical safety considerations.

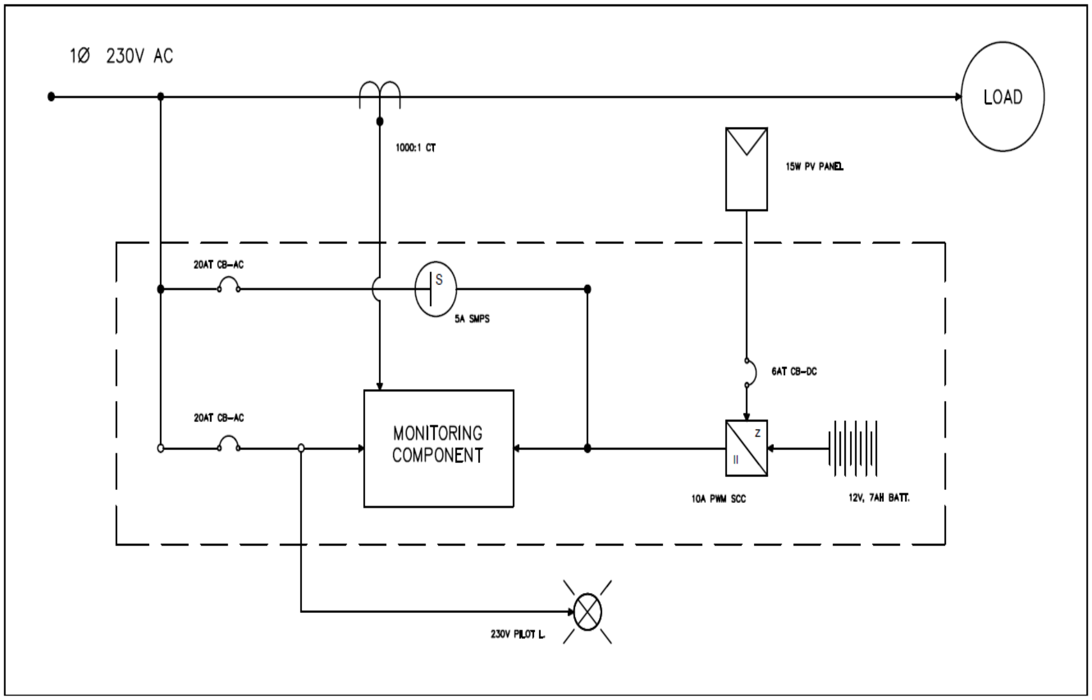

Fig. 2 Single-phase smart energy monitoring system

F. Wiring and Electrical Integration

The monitoring component has a reading capacity of 100A. To ensure circuit safety, according to Beltran (2014) [28], the conductor wire must have a minimum ampere rating set at 125% of the motor's full-load current, although the smart monitoring system only consumes a maximum of 0.1 ampere. Both the miniature circuit breaker and the circuit are designed with a single-phase 20-ampere trip rating (50-ampere frame), using THHN copper wire with a 3.5 mm² size, equivalent to #12 AWG.

This adheres to the guidelines outlined in the Philippine Electrical Code 2017 Ed., specifically in Section 2.40.1.6 (A) and Section 3.10.2.6 (B) (16). A switched-mode power supply (SMPS), in conjunction with a 20A AC circuit breaker, was implemented to ensure compliance with the safety and protection standards specified in IEC 61204-7:2016 [29]. In this context, the monitoring component registers a total of 0.1A, indicating that 1.024 mm² or #18 THHN wire should be used for the output terminals, as specified under NEC 310-16.

A NEMA 3R wall-mounted metal enclosure box, corresponding to IP24 type (IEC Classification) and with dimensions of 300 mm x 400 mm x 200 mm, was used to meet safety standards [30]. This type of enclosure is designed to prevent accidental contact with enclosed equipment and protect against falling dirt, rain, sleet, or snow. It includes drainage provisions, shields from rain above the lowest live part, and offers options for alternate locking and latching mechanisms [31]. Additionally, a 230V green indicator light was installed and mounted at the front, connected with 1.024 mm² or #18 THHN wire. The green light signifies active and functioning power, while its absence indicates a loss of power.

G. System Installation

During the experiments, the project was implemented in a residential dwelling in Guagua, Pampanga, under the operation of PELCO II. As outlined in Article 110.26 of the National Electrical Code, enclosed panel boards must be installed at a height of no more than 2.0 meters (6.56 ft). The monitoring system was wall-mounted near the main distribution panel to ensure Wi-Fi connectivity for seamless communication. In this study, the monitoring system was positioned at a height of 1.75 meters from the ground to the center of the enclosure, housing the device, with an approximately 8-meter wire distance to the CA0.5 utility meter.

The voltage pin connections were tapped from the load side of the main distribution breaker using 3.5 mm² THHN copper wires. The 100 A split-core current transformer, using 22 AWG silicone wire cables, was clamped onto a single main service conductor (line) located inside the distribution panel. The feeder wires were enclosed within a 20 mm Ø PVC conduit. To integrate the energy harvesting mechanism, the 15W monocrystalline solar panel was mounted on the dwelling's roof, supported by bolted aluminum z-brackets. Feeder wires of 18 AWG copper, connecting the PV panel and the monitoring system, were also enclosed in a 20 mm Ø PVC conduit.

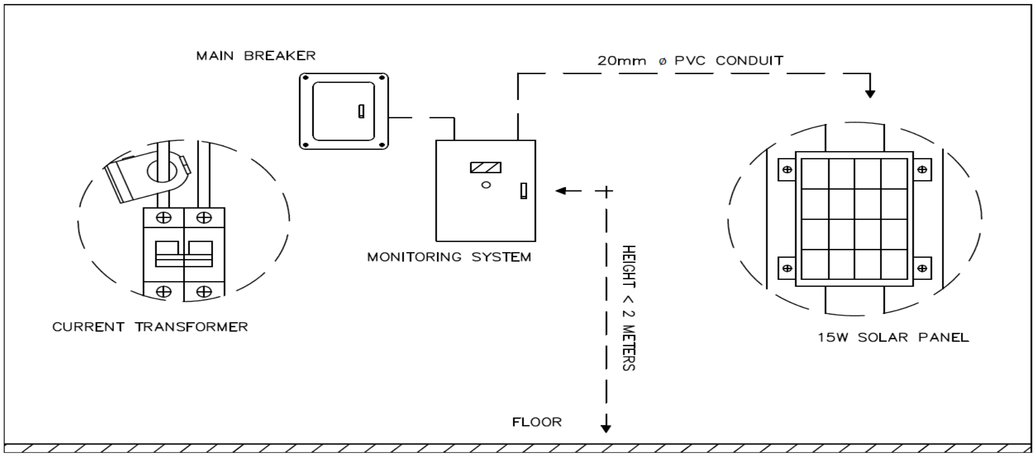

Fig. 3 Front elevation of system mounting & installation

H. Evaluation

The smart monitoring system was evaluated in comparison to a CA0.5 digital meter to determine its performance in real-time power and energy readings under typical residential loads. Errors in voltage, current, power, and energy readings were observed simultaneously in the following scenarios:

Case 1: Real-time performance of the smart monitoring system at a 500 W load.

Case 2: Real-time performance of the smart monitoring system at a 1500 W load.

Case 3: Real-time monitoring performance over a 1-hour duration.

Case 4: Energy performance of the smart monitoring system over a 1-month period.

Ten trials were conducted simultaneously for cases 1 and 2, with an approximate 20-second interval between each trial. Data collection involved instantaneously comparing readings from both the monitoring system and the meter, yielding average percentage errors for voltage, current, and power. For the energy assessment, the monitoring system was evaluated against the CA0.5 meter over a month-long period, comparing kWh readings. The evaluation periods were defined as quarters of the month from February 28, 2024, to March 28, 2024, with the final accumulated energy percent error being assessed. Comparing the monitoring system's performance with the CA0.5 utility meter is crucial for ensuring validity.

The American National Standard for Electric Meters, as specified in ANSI C12.1-2008, dictates that the in-service performance of watt-hour meters should be within a range of 98% to 102% registration accuracy, or ±2% error [32]. In this context, the solar-powered smart energy monitoring system will be tested against the CA0.5 digital meter. Determining the device's percentage errors relative to a calibrated distribution meter is essential for ensuring reliable operation. The percentage error [33] is computed using eq. (8).

$$\%\ Error = \frac{|\,Experimental\ value\ -\ Accepted\ value\,|}{Accepted\ value}\ x\ 100\% \quad (8)$$

I. Energy Generation Assessment

The determination of the photovoltaic system's energy generation and charging time needed to support the continuous operation of the monitoring system was carried out using eq. (9):

$$Energy\ Generated = Power\ rating\ (P) x\ hours\ (T) x\ efficiency\ (9)$$

The monocrystalline solar panels operate with an efficiency of 24% [34]. The sampled operating/sun hours for testing are 1 hour, 3 hours, and 4.5 hours. The energy consumption of the smart monitoring system is measured at 0.5 Wh.

J. Voltage Fluctuation Monitoring Assessment

Monitoring is conducted with records taken at 1-hour intervals over a 24-hour period to capture variations in voltage. This experiment, carried out on May 24, 2025, provides a comprehensive view of voltage stability within the dwelling. The nominal voltage for this installation is 230 V, which serves as the reference point for evaluating fluctuations. These fluctuations help in understanding load patterns and potential issues in the power supply [37].

III. RESULTS AND DISCUSSION

A. Reading Performance of the Monitoring System

Real-time voltage, current, and power readings are assessed using a nominal 230 V single-phase residential load setting of 500 W and 1500 W, compared against a CA0.5 digital energy meter over ten trials.

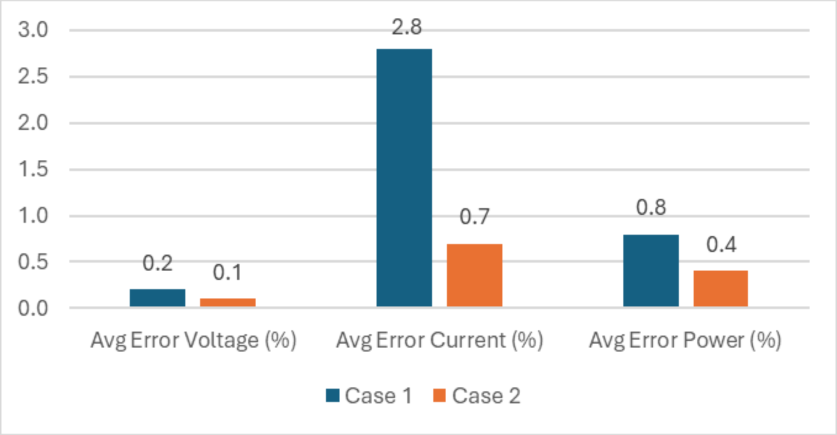

Fig. 4 Performance of the monitoring system in Case 1 and 2

In Case 1, with a 500 W load, the solar-powered smart energy monitoring system demonstrated impressive accuracy, with average power readings showing a 0.80% error, average voltage error at 0.17%, and average current error at 3.3%. In Case 2, with a 1500 W load, power readings improved to an average error of 0.40%, average voltage error of 0.08%, and average current error of 0.7%. Fig. 4 illustrates the acceptable power percent errors of the monitoring system, with average power errors within the ±2% registration accuracy indicated by ANSI C12.1-2008. The data also shows that the accuracy of the device improves with increasing load size, as demonstrated in Case 2, which exhibited a +0.4% increase in accuracy. The performance of the monitoring system appears to be dependent on the load, with fluctuations in accuracy observed across different load conditions. These findings underscore the system's ability to consistently provide standardized readings under varying loads.

TABLE I OBSERVATION OF REAL-TIME MONITORING PERFORMANCE AT 1-HOUR DURATION

Time	**Energy Monitoring System**			**CA0.5 Meter**			**Error Power**
	(V)	**(A)**	**(W)**	**(V)**	**(A)**	**(W)**	**(%)**
0:00	245.9	1.44	326.8	245	1.40	320	2.13
0:05	245.3	1.09	230.9	244	1.06	230	0.39
0:10	243.9	1.17	253.5	243	1.12	250	1.40
0:15	243.6	1.13	242.1	243	1.09	240	0.87
0:20	244.3	1.70	384.9	244	1.69	380	1.29
0:25	244.4	1.85	418.2	244	1.81	410	2.00
0:30	244.9	1.71	382.8	244	1.68	380	0.74
0:35	244.9	5.54	1353.5	245	5.51	1350	0.26
0:40	244.2	5.37	1307.7	244	5.34	1300	0.59
0:45	243.8	5.28	1283.6	244	5.26	1280	0.28
0:50	244.1	5.31	1291.9	244	5.28	1290	0.15
0:55	242.7	5.26	1273.2	243	5.23	1270	0.25
1:00	243.7	1.30	294.9	243	1.23	290	1.69

Table I presents the readings obtained from both the smart energy monitoring system and the digital meter at 5-minute intervals over the course of one hour. The power readings from both devices show variations over time, influenced by factors such as appliance usage and fluctuations in the electrical supply [35]. The percentage error in power readings ranges from 0.15% to 2.13%, demonstrating that the monitoring system performs within the accepted registration accuracy when measuring minimal loads but performs better with larger sampled loads.

Discrepancies in power readings between the monitoring system and the digital meter, as shown in Fig. 4 and Table I, can be attributed to differences in material specifications, installation practices, sensitivity levels, and calibration methods [36]. Utility meters are frequently calibrated to ensure high precision, whereas the monitoring system lacks such frequent calibration, highlighting the purpose of this baseline study. Electricity billing continues to be recorded by the utility meters, with the smart monitoring system serving primarily for tracking and real-time monitoring purposes for consumers.

TABLE II ACCUMULATED ENERGY (KWH) READING OVER 1-MONTH PERIOD

Period	Smart Monitoring System	CA0.5 Meter	Error Energy
	(kWh)	(kWh)	(%)
1	24.3	24	1.25
2	50.8	50	1.60
3	90.1	89	1.24
Final	122.3	121	1.07

Following four records taken at weekly intervals over a month, the solar-powered smart energy monitoring system registered a cumulative energy consumption of 122.3 kWh, compared to the 121 kWh recorded by the CA0.5 meter. The resulting percent error is 1.07%, meeting the ±2% criterion specified by ANSI C12.1-2008, given that the utility meter reports energy using only whole numbers. A month-long assessment is necessary to evaluate the device's capability for consumer monitoring.

B. Performance of the Photovoltaic Setup

The smart energy monitoring system's power requirement was measured at 0.5 W, establishing a 0.5 watt-hour specification. Concurrently, the 15 W monocrystalline solar panel delivers a 3.6 watt-hour output based on eq. (9). Table III displays the sampled sun hours alongside the corresponding energy generation of the solar panel (in watt-hours) and the energy consumption of the monitoring system (in watt-hours). The data demonstrates the solar panel's ability to consistently generate power, producing energy seven times greater than its consumption, and effectively meeting the energy demands of the device during daily operations. Lead-acid batteries have a 50% depth of discharge (DOD). At 0% DOD, the battery can provide 84 hours of continuous operation.

TABLE III ENERGY GENERATION AND CONSUMPTION

Sun Hours	Generation - Solar Panel	Consumption - Monitoring System
(Hrs)	(Wh)	(Wh)
4.5	16.2	2.25
3	10.8	1.5
1	3.6	0.5

The drained battery charges to 50% DOD after 11.5 hours of equivalent sunlight based on eq. (9). These findings indicate a reliable power supply for the smart energy monitoring system, enabling it to sustain and support continuous operation.

C. Voltage Fluctuation Monitoring and Significance

Monitoring the voltage helps protect equipment by ensuring it operates within optimal ranges, preventing overheating and inefficiency. It also optimizes energy consumption, reduces costs, and identifies power quality issues, thereby preventing disruptions and maintaining productivity.

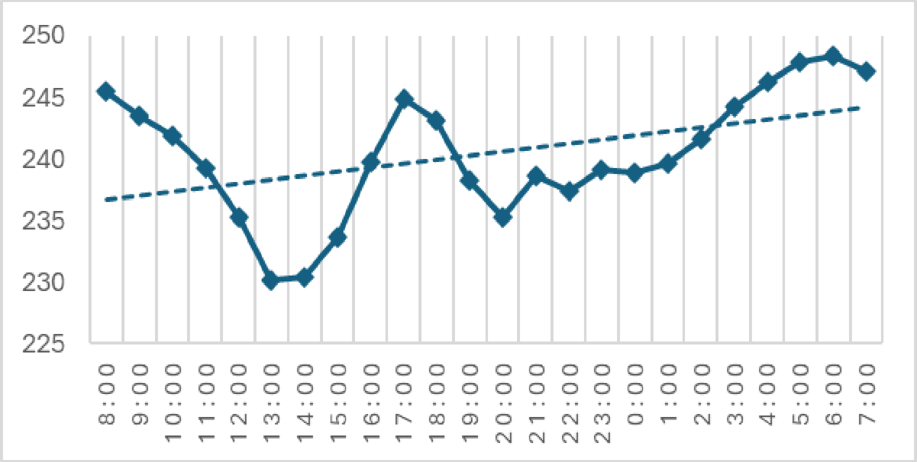

Fig. 5 Voltage variations of the installation at 1-day period

Fig. 5 shows significant voltage fluctuations recorded in a residential dwelling in Guagua, Pampanga. During peak afternoon hours (12:00 to 15:00) and evening hours (19:00 to 22:00), voltage levels are relatively low, with the lowest dips observed at 230.1 V at 13:00 and 230.4 V at 14:00. This decrease correlates with higher usage of electrical appliances and the consumption from other dwellings connected to the same network. Conversely, late-night and early-morning hours (03:00 to 09:00) exhibit stabilized and higher voltage levels, peaking at 248.4 V at 06:00, attributed to minimal appliance usage during these hours. These fluctuations underscore the importance of monitoring electrical loads to ensure a stable and reliable power supply. Voltage dips and sags can affect the performance, safety, and reliability of electrical equipment, as well as increase costs. Identifying these patterns helps in optimizing energy distribution and preventing issues caused by voltage instability, thereby maintaining household appliance efficiency and safety [37].

IV. CONCLUSION AND RECOMMENDATIONS

The assessment of the solar-powered smart energy monitoring system demonstrates sustained performance across various parameters, including real-time voltage, current, power, and energy, highlighting its effectiveness as a robust solution for real-time monitoring. Designed to operate within single-phase systems with a current threshold of 100 A, the system shows particularly strong performance with higher loads. The month-long energy reading assessment revealed the system's notable performance over an extended period, with accumulated percent errors within the ±2% standard. With its 15W monocrystalline photovoltaic supply, the device can generate energy seven times greater than its consumption and maintain independent operation for up to 84 hours using only the 12V lead-acid battery. Future research could focus on increasing the current reading capacity of the smart monitoring system and exploring its applicability to three-phase systems and industrial operations, which hold promise for handling heavier loads. Additionally, integrating solar technology into essential areas such as water and gasoline smart meters presents viable research opportunities. Enhancing the system's mobile interface and refining software features to facilitate more detailed monthly monitoring, resetting, and billing could further augment the system's effectiveness.

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