International Journal of Engineering and Information Systems (IJEAIS)
ISSN: 2643-640X
Vol. 10 Issue 5 May - 2026, Pages: 155-163

Design And Construction Of An Internet Of Things-Based Energy Metering System For Residential Application

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***Abstract**: Frequent increase in electricity tariff and estimation billing system have propelled customers of electricity in Nigeria to start seeking for diverse means to efficiently manage and monitor their energy consumption. One efficient, affordable and technological means recently discovered in managing and monitoring household electricity consumption in the country is usage of Internet-of-Things (IoT)-based energy metering system, which offers customers opportunity to remotely monitor and manage their energy consumption. In order to contribute to realisation of this laudable technology, the study presented in the paper developed an IoT-based energy metering system for residential application. The IoT-based energy metering system for this study was developed using PZEM-004T energy sensor and ESP32 microcontroller. The metering system was evaluated after its successful development. The result of the performance evaluation test conducted on the developed IoT-based energy metering system shows that the system performs favourable well with an average percentage voltage error of 0.43%, which is significantly lower than the recommended value in literature. In addition, the result of comparative performance analysis conducted by comparing the performance of the developed IoT-based energy metering system with similar developed meters shows that the developed energy metering system for this study performs favourably well with similar developed energy meters in literature. The overall result of the developed IoT-based energy system for this study shows that the developed energy metering system for this study does not only accurate but equally technically feasible for measuring and monitoring residential electricity parameters.*

Keywords: Electric power system; Electric meter; Electric meter classifications;

I. Introduction

Electric power system is a network of electrical components designed to effectively and efficiently generate, transmit, and distribute electricity to consumers. While the generation plant produces electricity at the generation station at low voltages in order to avoid stress on the armature of the alternator, the transmission of electricity is the responsibility of the transmission line at high voltage and low current in order to reduce electrical losses. On the other hand, the distribution of electricity basically is through the distribution system, which conveys electricity to the end-users or consumers that can be either residential homes or industries.

Over the past few decades, constant electricity supply is one of the critical issues in Nigeria. In actual fact, electrification of Nigerian's homes and industries is an issue as the total capacity of the electricity generation plants in Nigeria cannot meet the electricity demands of the Nigerian society. Even when the insufficient generated electricity is to be distributed, lack of ideal equipment and metering devices to overcoming electricity theft are another problem bedevilling electricity distribution in Nigeria. As reported in [1], metering of consumers' premises is essential in ensuring reliable and efficient electricity delivery because it helps in preventing electricity theft. Also, the authors in [1] stated that metering of consumers' premises is essential because it aids investors' attraction into the nation's electricity sector as well as encouraging customers to pay for electricity consumed.

However, recent revelation made by the Nigerian Electricity Regulatory Commission (NERC) shows that only 5,842,726 electricity customers, representing 44.39%, were metered in Nigeria as at December 31, 2023 while 13,162,527 representing 55.61% were unmetered. These unmetered customers only got their electricity bills through estimation billing system from the power distribution companies (Discos) in the country. This billing error and the cumbersome payment procedures in paying electricity bills in Nigeria according to [2] has also incapacitated Discos, which are electricity vendors in Nigeria, from running profitable business as well as serving customers effectively.

In most cases, observations had shown that most of the customers' premises that were metered were metered with obsolete electromechanical meters in which data collection and processing depend on humans. This means of data collection and processing that depend absolutely on human operator rather than automatic processing according to [3] is prone to error as its success depends on the operator's conditions. Furthermore, in house where digital and prepaid meters are installed, observations as reported in [2] revealed such meters were being bypassed by dubious consumers in order to steal electricity. In overcoming these challenges,

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integrating Internet of Things (IoT) in energy metering as reported in [4] has been observed as one of promising technologies for efficient monitoring and managing of electrical energy consumption.

Thus, the study reported in this paper was embarked upon with the aim of developing a functional IoT-based metering system, which can be remotely controlled and monitored energy consumption in Nigerians homes. This aim was achieved through the following three objectives. The first objective was the designing of the proposed IoT-based metering system. In the second objective, the designed IoT-based metering system in the first objective was developed and thereafter evaluated in order to evaluate its performance in the third objective. Detailed information on the development of the IoT-based metering system for this study is presented in under methodology. The rest of the paper is arranged as follows. Section II presents brief literature review on energy metering in Nigeria while section III discusses in detail the methodology involved in design and construction of the developed IoT-based metering system for the paper. In section IV, the results obtained when the developed IoT-based metering system was evaluated are presented and discussed while the paper is concluded in section V with summary of the findings.

II. Literature Review on Metering in Nigeria

Electric meter, also known as kilowatt-hour (kWh) meter is an electronic device that measures the quantity of electricity a home, a business or an electrically powered product consumes or uses [5, 6]. It operates by continuously measuring the instantaneous voltage and current. The product of these measured instantaneous voltage (volts) and current (amperes) according to [7] gives the instantaneous electrical power (watts), which is integrated over time or period to determine the energy used. Thus, the electric meters installed in customers' premises are being used by the electric utility for billing the customer.

Basically, electric or energy meters currently use in Nigeria can be classified into three basic categories or classes; namely electromechanical/induction energy meter, electronic energy meter and prepaid energy meter. Electromechanical/Induction energy meter is the oldest and most popular type of watt hour meter in Nigeria. This metering type is the traditional analog device for tracking or measuring electrical energy consume. The meter has rotating aluminum disc, which is mounted on a spindle between two (2) electromagnets. It uses electromagnetic fields to rotate an internal aluminum disc, which its speed is directly proportional to power consumed. The total accumulated rotations of the disc drive the mechanical dial of the meter to display the total kWh consumed. Typical picture of a single phase electromechanical or induction energy meter is as shown in Figure 1(a) while schematic connections of the both single-phase and three-phase of the meter type are shown in Figure 2(a) and Figure 2(b) respectively. One major disadvantage of this meter type is that it encourages estimated billing especially when power supply officer fail to read energy consumed by customer.

Figure 1: Picture of typical electromechanical meter

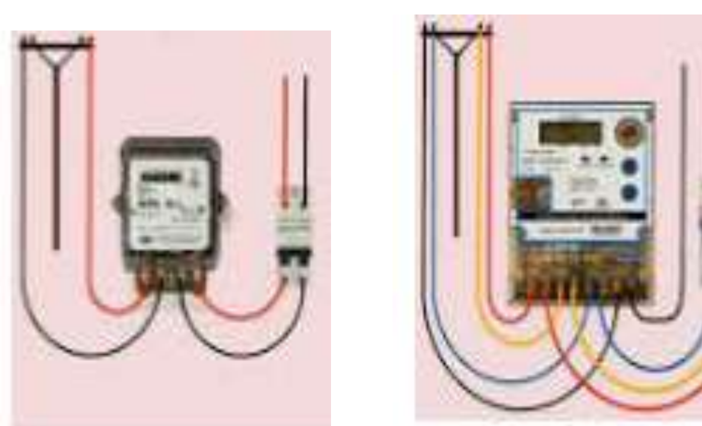

Figure 2: Connection of single phase electromechanical meter
Connection of three phase electromechanical meter

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On the other hand, electronic energy meter, which is shown in Figure 3, is a digital energy meter, which measures and records energy consume by the consumer. Unlike electromechanical or induction energy meter, electronic energy meter uses microchips and digital processors with no moving parts to provide accurate readings of the energy consumed as well as displaying the real-time amount of energy consumed on either a liquid crystal display (LCD) or light emitting diode (LED). The meter according to [5] is reliable, accurate and has high precision when compared to electromechanical or induction energy meter. The meter type also has potential to record other parameters such as the instantaneous values of the supply voltage, reactive power as well as the power factor. However, its usage is discouraged especially nowadays with widespread of non-linear loads, which hinders its accurate performance [8]

Figure 3: Typical electronic meter

Figure 4: Typical Smart/Prepaid energy meter

Prepaid energy meter, shown in Figure 4, is an advanced metering technology. The meter system according to [9] involves customers possess a credit in their electricity account before consuming energy supply by the utility provider or Discos. This implies that prepaid metering system connotes that customers pay for electricity in advance while their energy meters read or track their energy consumption and give the amount of their energy remain in their account in unit(s) form. Unlike both electromechanical energy meter and electronic meter, which are post-paid metering system, prepaid meter is a pay-as-you-go metering device whereby customers pay for the power before consuming it. One major advantage of prepaid meter over both electromechanical energy meter and electronic meter is that the metering system eliminates estimated billing.

Further observations in [9] reviewed that use of post-paid or billing metering system in Nigeria power system enhances both inefficient metring system and power supply. The authors in [9] also inferred that post-paid metering system when using both electromechanical energy meter and electronic meter in Nigeria encourages collection of illegal money from customers by the staff of various Discos in the country. On the other hand, disengagement from estimated billing system to prepaid metering system gives customers the opportunity to pay for actual energy consumed. Findings of authors in [10] also revealed that prepaid metering system eases or enhances revenue collection for various distribution companies or Discos in the country while consumers can equally manually monitor their energy consumption and manage their budget appropriately. It was also revealed in [11] that adoption of prepaid metering system in Nigeria reduces the level of personal contacts between the officers of the energy distribution companies, Discos, and customers since officials of energy distribution companies need not to visit customers' promises for data collections.

However, observations have shown that some dubious customers with prepaid meters are bypassing their meters in order to steal electricity. In order to overcome this energy theft and revenue losses as well as enhances efficient energy management by customers, use of automation system was suggested in [7]. Similarly, integration of Internet of Things (IoT) in energy metering as reported in [4] has been observed as one of promising technologies for efficient monitoring and managing of electrical energy consumption. This is because automatic control of home appliances remotely when customers are away from homes via IoT offers customers efficient remote monitoring and managing of their energy consumptions. Thus, this study was embarked upon with the aim of developing a functional IoT-based metering system, which can be remotely controlled and monitored customers' energy consumption. The methodology employed in achieving the aim as well as the stated earlier objectives of this study is presented in next section of this paper.

III. Methodology

The section presents in details the design, implementation and evaluation of the developed IoT-based energy metering system for this study. The methodology employed includes the system design and architecture of hardware and software components, system implementation and performance evaluation. The aim is to ensure that the developed system is reliable, efficient and can accurately measure electricity parameters in real-time. The hardware components for this study were carefully selected to ensure the system's functionality and compatibility with the IoT framework. Similarly, the software packages and applications employed in this study were such that enable the real-time energy monitoring and controlling. The step-by-step approach employed in developing the IoT metering system for this study is shown in Figure 5. Likewise, the flow chart for the developed IoT metering system for this study is shown in Figure 6. The uniqueness of the developed IoT metering system for this study is that it does not only transmit data or information to user via short message service (SMS) alone but can equally relay information via email.

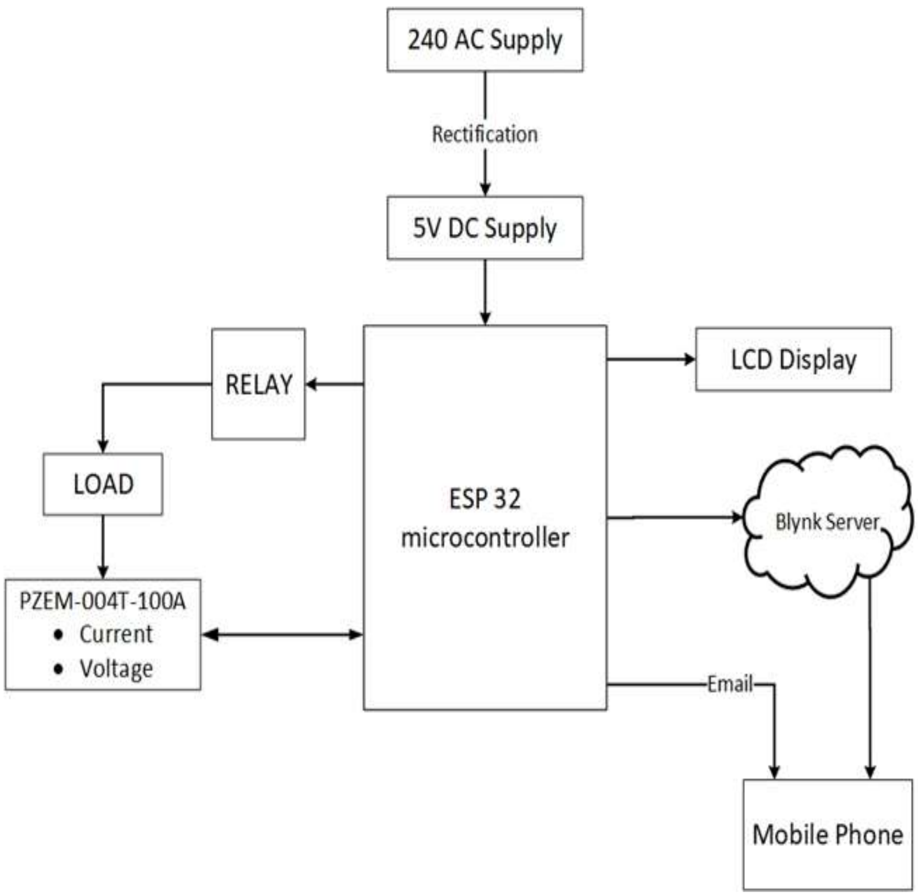

Figure 5: Systematic block diagram of the developed metering system

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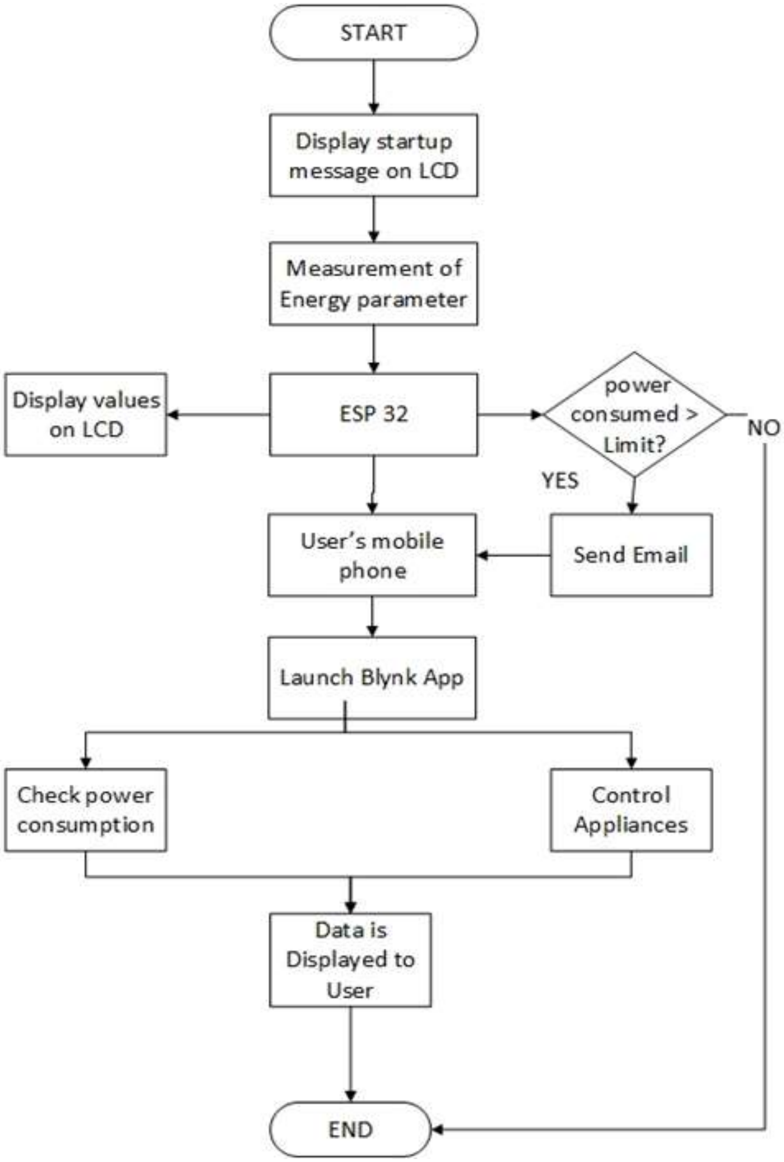
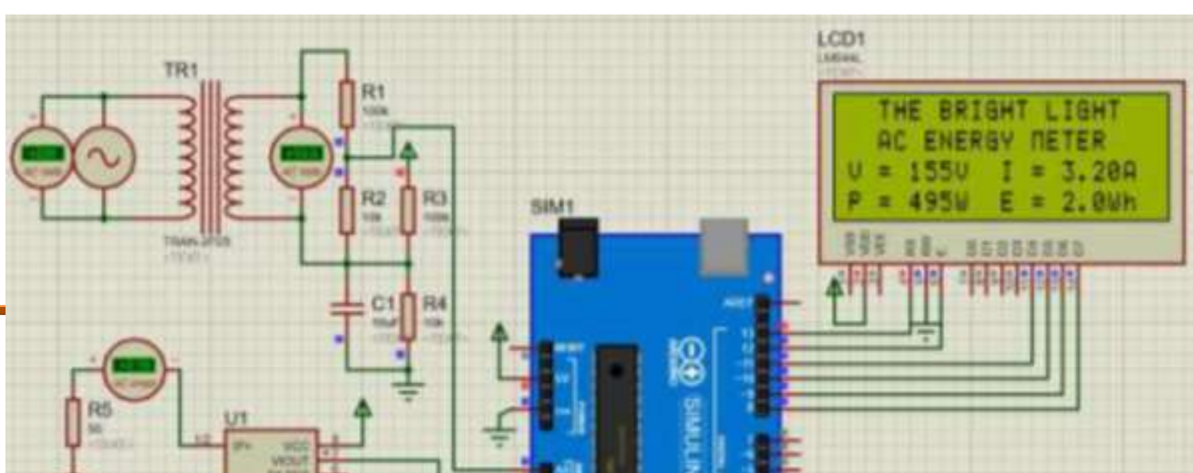


Figure 6: Operational flow chart for the developed metering system

Implementation of the designed circuit for developed IoT-enabled metering system for this study integrated ESP32 microcontroller with PZEM-004T-100A energy sensor module, relay module, and LCD screen. The components are connected to ensure seamless data acquisition, processing, and communication. The simulation circuit diagram presented in Figure 7 ensures that the system can measure voltage and current and thus computes power consumption, display real-time data, and control loads via relays.



The PZEM-004T-100A energy sensor employed in the circuit was thereafter calibrated to ensure accurate measurements of current, voltage, power and energy. The first calibration process involved measuring the voltage across the load. The output from the PZEM-004T was compared with the multimeter readings to ensure there were no discrepancies with the multimeter readings. The current calibration was the second calibration process. This was conducted by inserting shunt resistor in series with 100 Watt bulb to ensure accurate current measurement with the multimeter. Similar to the voltage calibration, the current readings from the PZEM-004T were compared with those obtained from the multimeter till there were no deviations.

After calibrating both voltage and current, the power factor was also verified by using a known resistive load and calculating the expected power consumption. The PZEM-004T's power readings were compared with the calculated values based on the voltage and current measurements. Lastly, energy accumulation was tested by running the circuit for a specific duration while monitoring the energy consumed. The total energy recorded by the PZEM-004T energy sensor employed was compared with the energy calculated from the known values of voltage, current, and time. The essence of the comprehensive calibration conducted was to ensure that the PZEM-004T-100A energy sensor provided reliable and precise readings for the IoT-based energy metering system. After the successful completion of the developed IoT-based metering system, which its picture is shown in Plate 1, the developed system was evaluated. The results of the various performance evaluation tests conducted were presented and discussed in the next section.

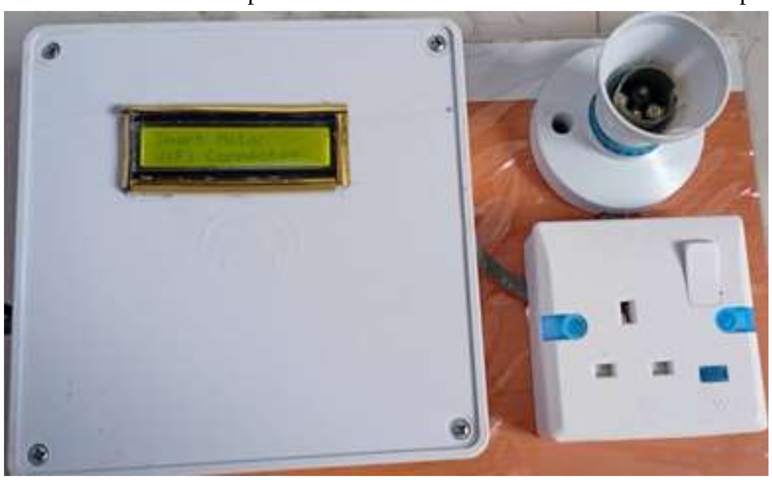


Plate 1: The developed IoT-based metering system with evaluating ports

IV. Results and Discussion

The section presents detailed information on obtained results, which were also discussed, when the developed IoT-based metering system for this study was evaluated. The developed system was actually evaluated to ascertain the accuracy of its measurement and its response time in updating a change in electricity supply status to the Blynk cloud using a 60 W filament bulb, 100 W filament bulb, and 500 W pressing iron load. However, only the result obtained when the developed system was evaluated using 100 W filament bulb is presented in this paper due to limited space. Two specific tests were actually conducted to evaluate the performance of the developed system. The first was actual performance evaluation test for the developed energy system while the second test conducted was a comparative performance evaluation test. Detailed information on the two tests namely; actual performance evaluation test and comparative performance test, conducted to evaluate the performances of the developed system is presented in the following sub-sections.

Actual Performance Evaluation Test

This actual performance test on the developed IoT-based metering system was conducted by connecting a 100 W filament bulb to the socket outlet provided on the system in Plate 1. Voltage, current, and power values obtained when the performance evaluation test was conducted using both the developed energy meter and a digital multimeter for duration of 10-minute were recorded. The data obtained for both the developed system and the mulltimeter meter are plotted and presented graphically in Figure 8.

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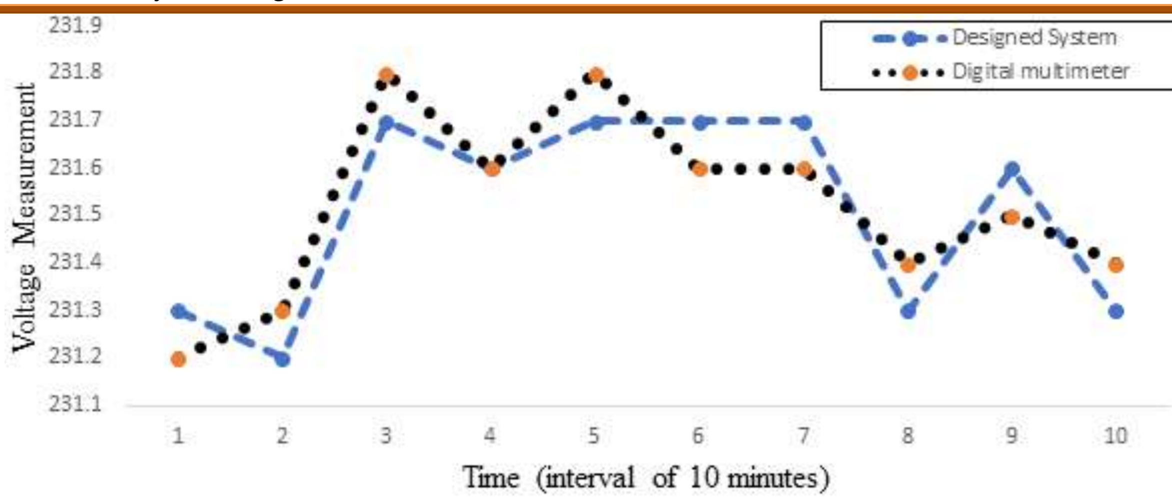

Figure 8: Performance evaluation result of the developed IoT-based metering system

Critical observation of Figure 8 shows clearly that the voltage measurement readings captured by developed system are in close proximity with measurement readings by the digital multimeter. This implies that the developed IoT-based metering system performances favourably well with the multimeter. The data obtained were further analysed by computing the percentage voltage error between the obtained values for the developed system and the digital mulltimeter using the mathematic percentage error expression in [12] as;

$$Error\ (\%) = \frac{Measured - Reference}{Reference} \times 100\% \quad (1)$$

The computed percentage voltage error obtained was 0.039%. This negligible percentage error value implies that the developed IoT-based metering system is accurate with extremely close values to the values measured by the standard meter. The result further confirmed the reliability of the developed IoT-based metering system.

The accuracy and reliability of developed IoT-based metering system for this study is confirmed by the established fact in the study presented in [13] where the authors stated that any developed electrical energy monitoring system that employs PZEM-004T energy sensor module is accurate and reliable as long as its average error value is less than 2%. Similarly, study reported in [12] revealed that any electrical monitoring system using PZEM-004T energy sensor with an average error rate of 1.19% compared with the reference measurements is technically feasible for practical household energy monitoring. Hence, with 0.039% error value for the developed energy metering system for this study, which is far below the reported value, indicates that developed energy metering system for this study is not only accurate but equally reliable and technically feasible in measuring or monitoring residential electricity parameters.

Comparative Performance Evaluation Test

In order to further evaluate the performance of the IoT-based energy metering system developed for this study, the result obtained were compared with similar developed energy metering systems in literature. The choice of the studies employed in conducting the comparative study was based on usage of the same energy sensor module. The comparative result obtained is presented in Table 1.

Table 1: Comparative performance evaluation result

Existing Works	Sensor Module Used	Avg. Voltage Error (%)
Reference [12]	PZEM 004T	1.19
Reference [13]	PZEM 004T	< 2.00
Reference [14]	PZEM 004T	0.5

Reference [15]	PZEM 004T	0.616
Developed system	PZEM 004T	0.43

The comparative performance evaluation result presented in Table 1 compares the percentage error for maximum voltage obtained from load test of the developed IoT-based energy system for this study with other four similar studies in literature. The choice of the reference studies was based on usage of same sensor module. The comparative result as presented in Table 1 shows that the average voltage percentage error for this study is not only within the recommended range in literature but was the lowest of all the four studies considered. The comparative result thus shows that the developed IoT-based energy system for this study is not only accurate but equally technically feasible for measuring or monitoring residential electricity parameters. The comparative analysis also shows that data from developed IoT-based energy system for this study is reliable, valid and can compared favourably with results or data from similar studies literature.

V. Conclusion

The study presented in this paper has demonstrated that IoT-based energy monitoring system developed using PZEM-004T energy sensor and ESP32 microcontroller for this study can both reliably and accurately measure residential electricity consumption in real-time. The developed IoT-based energy monitoring system achieved an average voltage percentage error of 0.43% compared with a calibrated reference voltage reading measured with digital standard multimeter. This low percentage error value indicates that the developed IoT-based energy monitoring system is reliable and technically feasible to measure residential electricity parameter. The result obtained from the comparative analysis conducted to validate the developed IoT-based energy monitoring system shows that the developed system performs favourably well with similar studies in survey literature.

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