Development of a web-based single-phase load monitoring and auditing system

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Article Info

Article history:

Received Oct 8, 2021
Revised Jun 6, 2022
Accepted Jul 1, 2022

Keywords:

Consumer
Energy consumption trend
Load monitoring and billing system
Nigeria
Utility

ABSTRACT

In a developing nation like Nigeria, the conventional load monitoring and billing system has proved to be tedious, time-consuming, expensive, and prone to human error over the years. Therefore, this creates the need for an efficient system that can assist the Utility to monitor the energy consumption trend of the customers remotely. This work developed a web-based single-phase load monitoring and auditing system using NodeMCU (ESP8266) microcontroller, PZEM-004T sensor, and liquid crystal display (LCD) module for the hardware unit and Blynk internet of things (IoT) platform for the software unit. The system design was implemented around the ESP8266 microcontroller with relevant design models, and standard power and energy equations programmed into the microcontroller in the Arduino integrated development environment. The developed system was load tested to examine its performance and determine its reading error. The hardware and software units of the system operated satisfactorily when tested. The reading accuracy for current and voltage measured by the device were ±0.2% and ±0.4%, respectively, giving a reading error of ±0.8% for power measurement. The developed system is suitable for residential, commercial, and similar applications where the energy usage trend of some small loads is required for management purposes.

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1. INTRODUCTION

Globally, the operation of the electrical energy system with its associated components has been of great importance in the running of day-to-day activities of every man [1]. Since the generation of electrical energy, it has proved to be a critical resource for various human activities, supporting customers' lifestyles in today's technologically advanced and industrialized society [2], [3]. Electricity generation in Nigeria dates back to 1929 when the Nigerian government mandated the Nigerian Electricity Supply Company to establish a hydroelectric power station at Kura, Jos [4]. Electricity distribution, which involves supplying, monitoring, and auditing electrical energy consumed by end-users, also commenced alongside electric power generation [5], [6].

The national electric power authority (NEPA) was the institution governing electricity use in Nigeria before being changed to power holding company of Nigeria (PHCN) in 2005. Following the privatization introduced by the Nigerian government in 2013, the electricity distribution sector was decentralized into 11 distribution companies (Discos), including Abuja Electricity Distribution Company, Benin Electricity Distribution Company, Enugu Electricity Distribution Company, Ibadan Electricity Distribution Company, Jos Electricity Distribution Company, Kaduna Electricity Distribution Company, Kano Electricity Distribution Company, Eko Electricity Distribution Company, and Ikeja Electricity Distribution Company among others [7].

One of the important activities for the successful running of any electrical distribution system is load audit. It is the process by which energy consumed in a facility is determined [8]. In various cities in Nigeria, load audit by Discos usually involves the installation of the electromechanical energy meter at the main supply switchgear or other key locations in the customers' premises. The meter, which is also employed for billing purposes, measures the current and voltage used by the customers' loads over some time and it is usually calibrated in kilowatt-hour (kWh) [9], [10].

Conventionally, the auditing process requires trained technical personnel of a particular distribution company visiting consumers in their various houses to take load readings on the installed energy meter and log the readings manually for further processing [11]. The energy bill is prepared according to the utility service tariff applicable to each end-user. Subsequently, the marketing personnel of the distribution company goes door to door to distribute the fully prepared bill slips to the respective consumers. The monthly energy consumption reports issued to the consumers are inadequate for planning conservation programs or assessing the impact of the conservation programs once implemented [12]. This is largely attributed to possible human error introduced during the auditing process resulting in an inefficient billing and unnecessary slow response or delay of the consumers receiving prompt feedback on energy consumed from the utility company [13]–[15]. Therefore, the need for an automated system such as the web-based load monitoring and auditing system developed to provide more frequent updates becomes highly imperative.

A web-based technology can improve the utility's business operations. Apart from providing an enabling environment for a robust and secure exchange of information between the utility and the customers, it can assist the utility in the aspects of energy conservation, administration control, and auditing process [16]–[18]. A web-based load monitoring and auditing system in this line will encompass information technologies, telecommunications, automation, and other computational tools, allowing the distributed storage of information that can provide useful insights into the users' loads. Therefore, in this work, a web-based single-phase load monitoring and auditing system was designed and developed.

2. AUTOMATED ENERGY METER

Conventional electromechanical energy meters are gradually becoming obsolete in most countries, including Nigeria, and are now being replaced by the more technologically advanced electronic meters to enhance the metering process and energy billing system [19], [20]. An automated energy meter is a device that remotely obtains the customers' energy consumption data and transmits the data to the Utility controlled database for different administration purposes [21], [22]. According to the literature, many potent technologies are being integrated into the electronic meters to produce more efficient systems. Islam and Bhuiyan [22] designed and implemented a smart energy meter for data acquisition and tampering detection using Raspberry Pi. Patil *et al.* [23] designed and developed a microcontroller-based prepaid energy meter. Veloso *et al.* [24] produced an internet of things (IoT) smart metering solution using IEEE 802.15.4, a technical standard that defines the operation of low-rate wireless personal area networks (LR-WPANs). Joshi *et al.* [25] developed a microcontroller-based smart energy meter. Oyubu and Nwabueze [26] designed and constructed a smart energy metering system using global system for mobile communication (GSM) modem. Gopinath *et al.* [27] built an embedded digital energy meter using the ZigBee technology. The literature has shown that several research works have been carried out on the deployment of web-based technology for load monitoring and auditing. However, it appears little or no attention has been paid to remedial action that could be taken against erring or defaulting consumers by the utility company. Hence, the system designed incorporated a disconnecting unit that could assist the utility company in de-energizing any erring or defaulting consumer from the source of supply through the Blynk platform.

3. METHOD

3.1. System overview

The basic building blocks of the web-based single-phase load monitoring and auditing system developed are shown in Figure 1. The system consists of two units: hardware and software parts. The hardware part comprises a PZEM 004T sensor, which measures the user's load current and voltage and feeds the readings to the NodeMCU (ESP8266) microcontroller, the heart of the load monitoring and auditing system. The microcontroller converts the measured current and voltage into equivalent power and energy readings through programmed power and energy equations and displays the readings on the liquid crystal display (LCD) screen. The readings are transmitted to the utility database via the web.

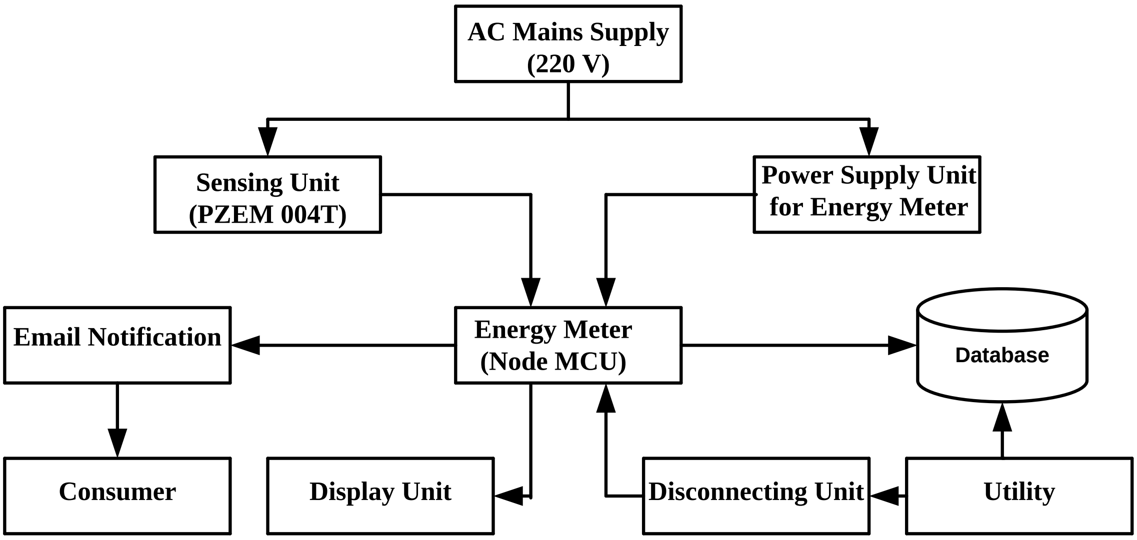


Figure 1. Block diagram of the developed web-based single-phase load monitoring and auditing system

The software part is a Blynk IoT platform, a combination of the Blynk database to store current, voltage, power, and energy consumed over time as measured by the system and a graphical user interface (GUI) for interaction with the system. An email notification is also sent to the consumer from the Blynk application. The disconnecting unit assists the utility company in de-energizing any erred or defaulting consumer from the source of supply through the Blynk platform since each consumer is fully registered with the company, and their documented profile may be used to trigger this unit on the system.

3.2. System hardware design

3.2.1. Power supply unit

Figure 2 shows the power supply unit for the web-based single-phase load monitoring and auditing system developed in this work. A 220/12 V transformer was employed at the input section of the circuit to step down the 220 V from the AC mains supply to 12 V. The 12 V AC source output, which is not suitable for use by most components in the circuit, being DC powered and of lower voltage is further rectified, filtered and regulated to produce the 5 V DC desired for the system operation.

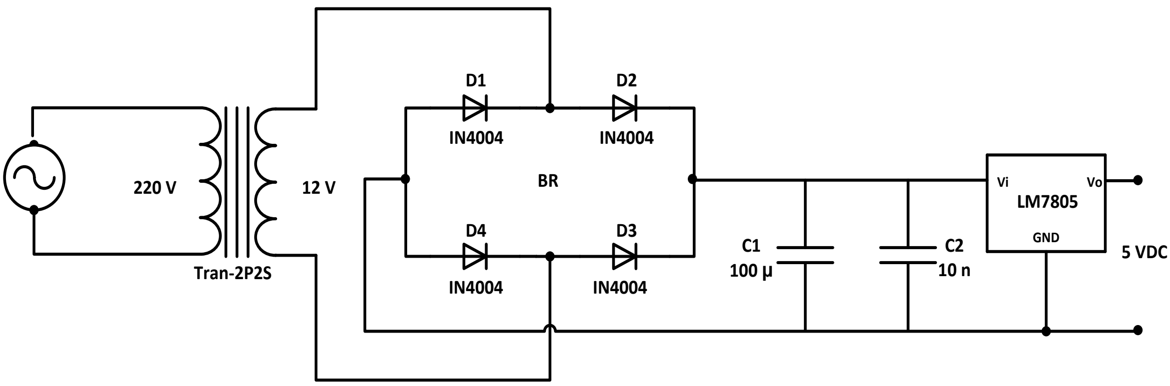


Figure 2. Circuit diagram of the power supply unit for the web-based single-phase load monitoring and auditing system

For the filtering process, the size of the filtering capacitor was obtained using (1) to (4) [28].

$$C = \frac{It}{V} \tag{1}$$

$$t = \frac{1}{4f} \tag{2}$$

$$V = \sqrt{2V_{rms}} - V_d \tag{3}$$

$$C = \frac{1}{4f\sqrt{2V_{rms}} - V_d} \tag{4}$$

Where:
C : the required size of the filtering capacitor,
I : the maximum current available in the circuit,
T : the period for the complete rectification cycle, V is the rectified voltage,
V_{rms} : the step-down voltage output from the transformer,
V_d : the forward voltage of the rectifier,
f : the frequency of the AC mains supply.

The use of I, V_{rms}, V_d and f as 500 mA, 12 V, 1.4 V, and 50 Hz respectively in (4) gave C as 160.56 μF. However, a capacitor of about 100 μF is sufficient for this filtering process. Hence, capacitor C_1 in Figure 2 was chosen as 100 μF. The capacitor C_2 of 10 nF was employed further to smoothen the output voltage from the rectification unit. Since 5 V DC is the voltage desired for the internal operation of the overall system, the LM7805 voltage regulator was used to regulate the filtered 12 V output from the rectification unit to 5 V DC.

3.2.2. Control unit

The main component of the unit is NodeMCU (ESP8266) microcontroller. Data collection and overall circuit design were implemented around the microcontroller. It processes the current and voltage values obtained from PZEM-004T sensor to produce power and energy readings which are subsequently sent to the Blynk database for storage and LCD screen for display. The basic power and energy expressions coded in the microcontroller for the conversion of current and voltage into equivalent power and energy consumed by the user's loads over some time are given (5) and (6), respectively [29].

$$P = IV\,cos\theta \tag{5}$$

$$E = Pt = IV\,cos\theta \tag{6}$$

Where P, E, t and $cos\theta$ respectively, denote the active power used by the loads, the energy consumed by the loads, the period for which the power is consumed, and the system power factor which was considered 0.8.

The overall circuit diagram of the developed web-based single-phase load monitoring and auditing system with the NodeMCU (ESP8266) microcontroller as the control unit is shown in Figure 3. The LCD employed was 16 by 2 characters module. It was interfaced to the microcontroller with an I^2C device that converts a parallel communication protocol using multiple pins to a serial communication protocol using only two pins, one for serial data (SDA) and the other for serial clock (SCL). This helps keep connections simple and saves more pins for other uses.

More so, 30 A electromechanical relay was used for the disconnecting unit. The design's choice of a 30 A rating for the relay resulted from its ability to disconnect a high-capacity facility. The utility company, through this relay, could disconnect any consumer found wanting, for instance, when such consumer fails to pay up the bill of energy consumed for a specified period. The load-control button on the Blynk interface created at the utility's end allows easy operation of this mechanism. When the button is toggled off, the power supply is disconnected at the user's end. Also, when the button is toggled on, the power supply is connected, and electricity is supplied to the user.

3.3. System software design

The major design activities implemented in this section of the work were in two folds. The first activity involved coding power and energy expressions of (5) and (6) in the NodeMCU microcontroller for current, and voltage conversion into equivalent power and energy readings in the Arduino integrated development environment using C# programming language. The second activity involved creating the database to track and record users' energy consumption and the graphical user interface to facilitate easy interaction between utility's database and the user's load monitoring and auditing system using the Blynk IoT platform.

Blynk is an open-source application designed based on the IoT for iOS or Android smartphones to control Arduino, Raspberry Pi, and NodeMCU through the internet. It can control hardware remotely, display sensor data, and store and visualize data, among other important functions performed. The flow chart showing the interaction between the hardware and software units for the overall system operation is presented in Figure 4.

3.4. Testing of the developed system

Having developed the web-based single-phase load monitoring and auditing system, the device was tested using an OX fan of 125 W rating as a sample load to examine the performance of various sections, including the sensing unit, power supply unit, control unit display unit, and the Blynk application. The reading error of the system was also determined.

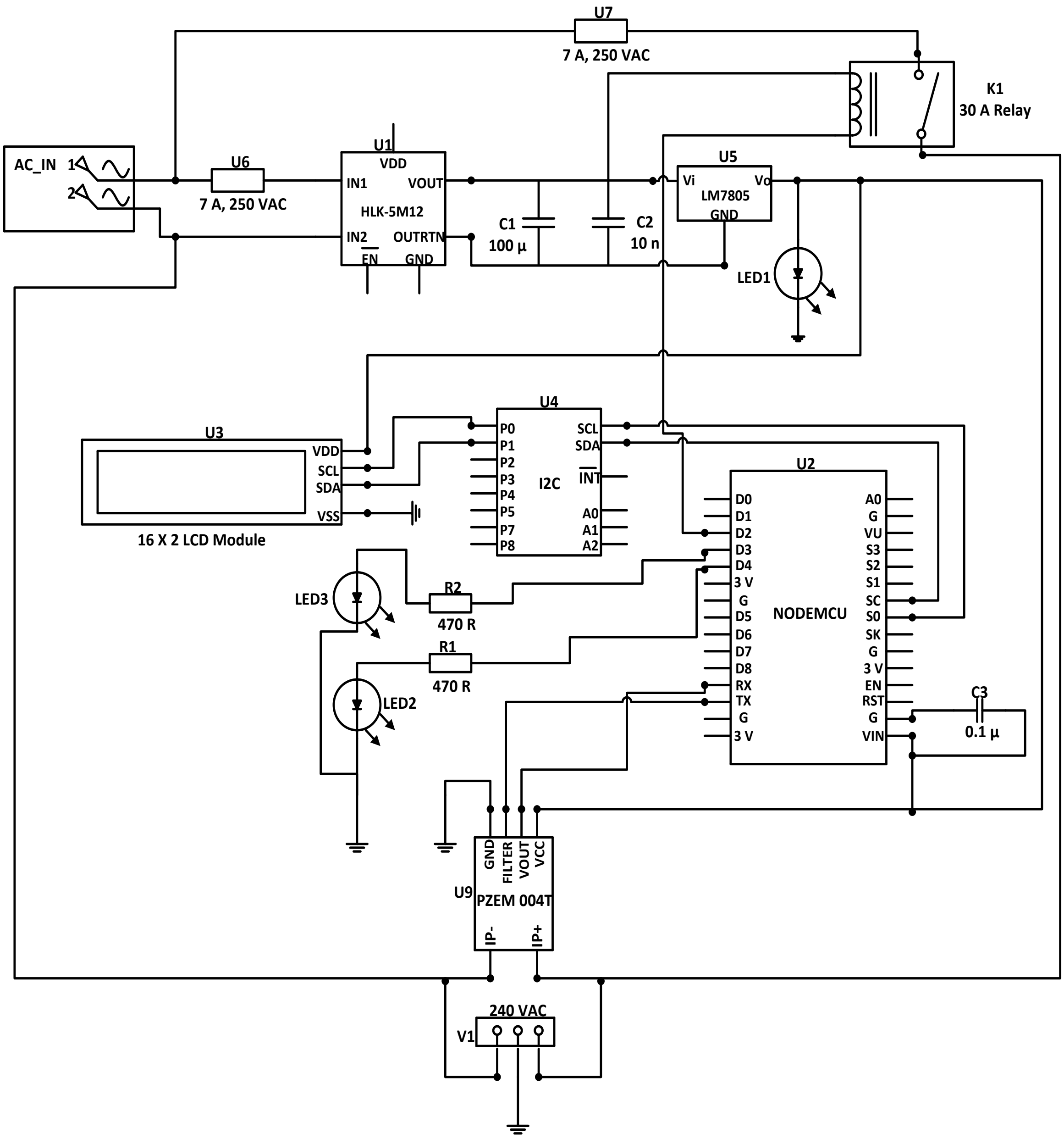


Figure 3. Circuit diagram of the web-based single-phase load monitoring and auditing system

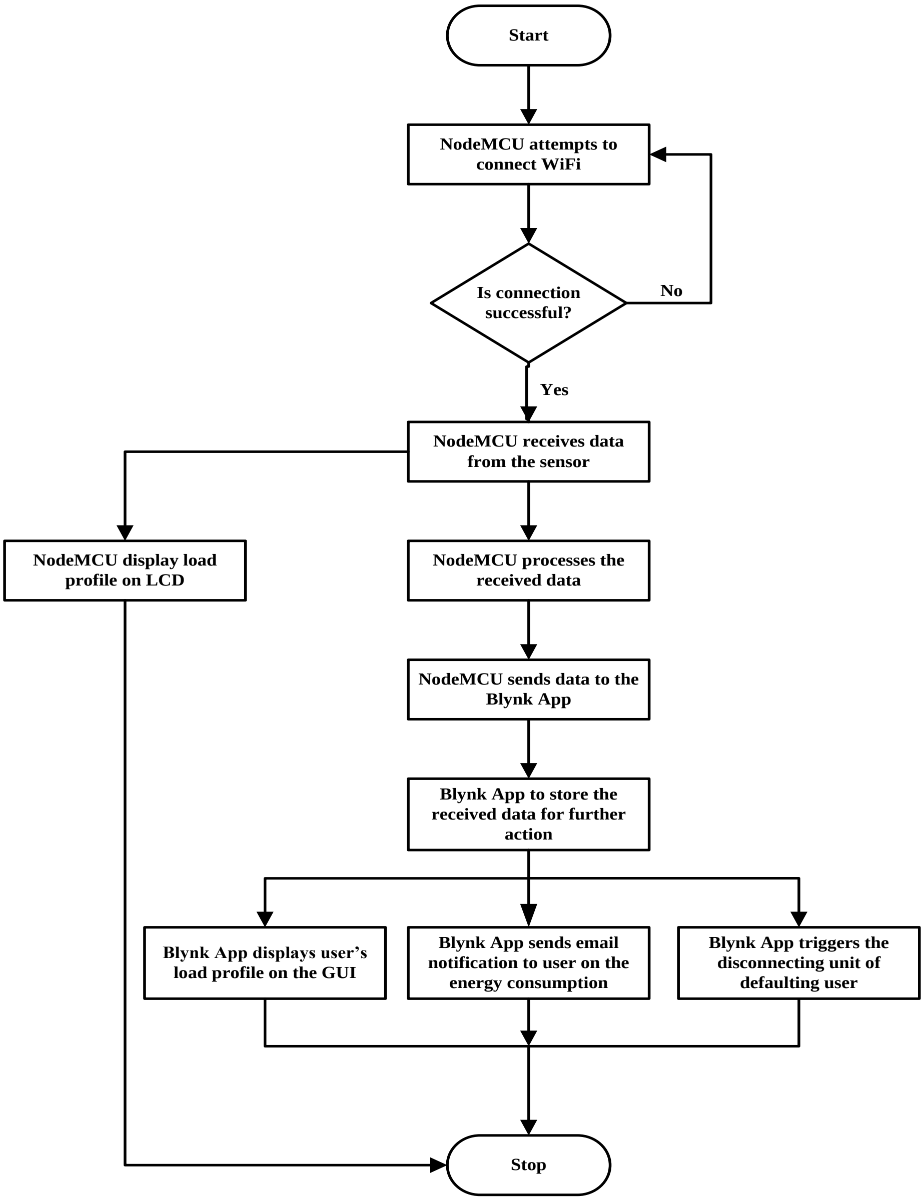


Figure 4. Flow chart for the system operation

4. RESULTS AND DISCUSSION

4.1. The developed system

The constructed model of the web-based single-phase load monitoring and auditing system is presented in Figure 5, while its internal circuitry is shown in Figure 6. Figure 5 simply depicts the external features of the system comprising the casing, the display unit and the connecting unit consisting the power input and output cables. Figure 6 shows how the components such as the HLK power module, the NodeMCU microcontroller, PZEM-004T sensor, relay and I^2C module making up the developed system are interconnected on the printed circuit board.

4.2. Performance test results

Figure 7 shows the developed web-based single-phase load monitoring and auditing system during performance testing, while Figures 8-10 show the resulting Blynk GUI, data logging on the database, and the sent email notifications. It was observed from Figure 7 that the developed web-based single-phase load monitoring and auditing system was fully functional when tested. The LCD displayed the load profile (current, voltage, power, and energy readings) of the OX fan used as the test load.

Figures 7 to 9 showed that the software unit of the system was active and effective in carrying out its designed objectives, which involve load profile display on the Blynk interface, data storage on the database, and sending continuous email notifications to users on the energy consumption record. The load data in Figure 8 was opened with Microsoft Excel for easy access and analysis. These records could only be accessed by the assigned utility personnel and used for further action. Using the multimeter readings as a reference, the current and voltage reading errors of the developed web-based single-phase load monitoring and auditing system were evaluated as ±0.2% and 0.4%, respectively, giving a power reading error of ±0.08%, which is considered tolerable for most metering devices.

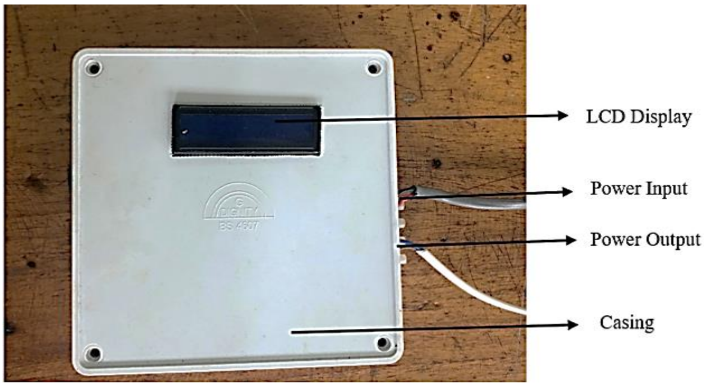


Figure 5. The developed web-based single-phase load monitoring and auditing system

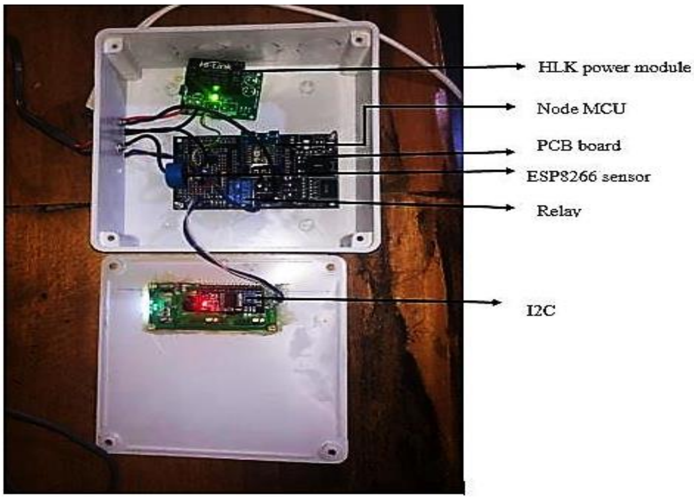
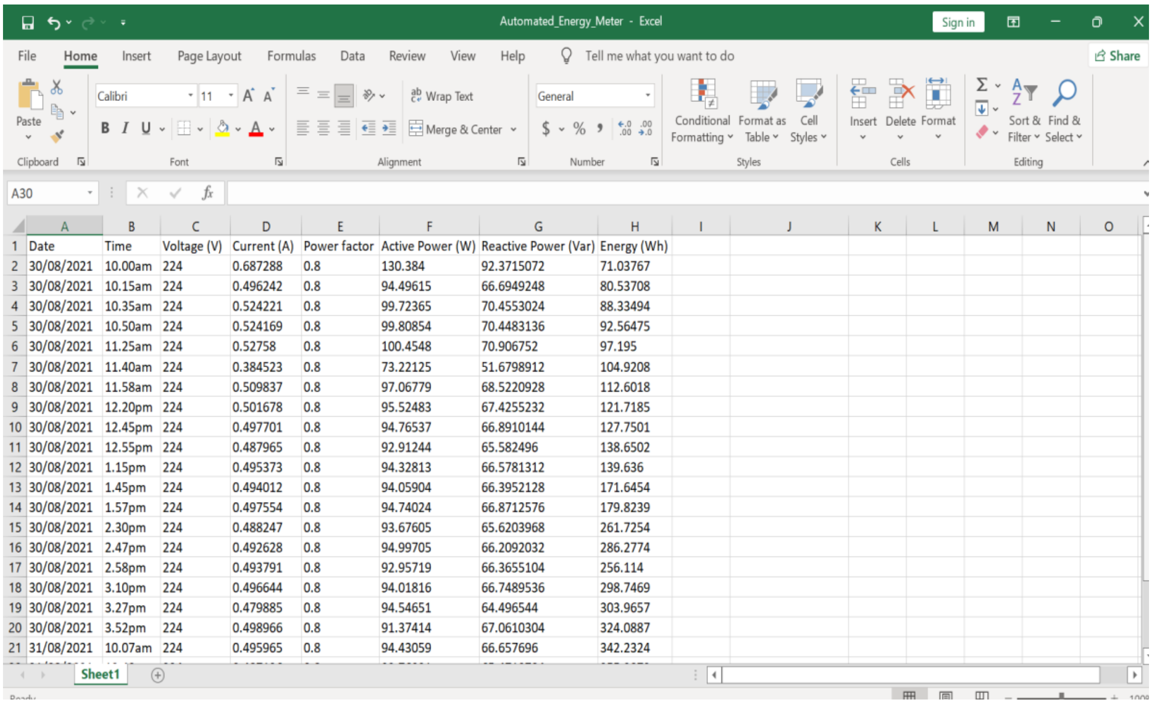


Figure 6. The internal circuitry of the smart energy meter

Figure 7. Performance testing of the developed system

Figure 8. Blynk GUI during performance testing



Date	Time	Voltage (V)	Current (A)	Power factor	Active Power (W)	Reactive Power (Var)	Energy (Wh)
30/08/2021	10.00am	224	0.687288	0.8	130.384	92.3715072	71.03767
30/08/2021	10.15am	224	0.496242	0.8	94.49615	66.6949248	80.53708
30/08/2021	10.35am	224	0.524221	0.8	99.72365	70.4553024	88.33494
30/08/2021	10.50am	224	0.524169	0.8	99.80854	70.4483136	92.56475
30/08/2021	11.25am	224	0.52758	0.8	100.4548	70.906752	97.195
30/08/2021	11.40am	224	0.384523	0.8	73.22125	51.6798912	104.9208
30/08/2021	11.58am	224	0.509837	0.8	97.06779	68.5220928	112.6018
30/08/2021	12.20pm	224	0.501678	0.8	95.52483	67.4255232	121.7185
30/08/2021	12.45pm	224	0.497701	0.8	94.76537	66.8910144	127.7501
30/08/2021	12.55pm	224	0.487965	0.8	92.91244	65.582496	138.6502
30/08/2021	1.15pm	224	0.495373	0.8	94.32813	66.5781312	139.636
30/08/2021	1.45pm	224	0.494012	0.8	94.05904	66.3952128	171.6454
30/08/2021	1.57pm	224	0.497554	0.8	94.74024	66.8712576	179.8239
30/08/2021	2.30pm	224	0.488247	0.8	93.67605	65.6203968	261.7254
30/08/2021	2.47pm	224	0.492628	0.8	94.99705	66.2092032	286.2774
30/08/2021	2.58pm	224	0.493791	0.8	92.95719	66.3655104	256.114
30/08/2021	3.10pm	224	0.496644	0.8	94.01816	66.7489536	298.7469
30/08/2021	3.27pm	224	0.479885	0.8	94.54651	64.496544	303.9657
30/08/2021	3.52pm	224	0.498966	0.8	91.37414	67.0610304	324.0887
31/08/2021	10.07am	224	0.495965	0.8	94.43059	66.657696	342.2324

Figure 9. The data extracted from the Blynk database during testing

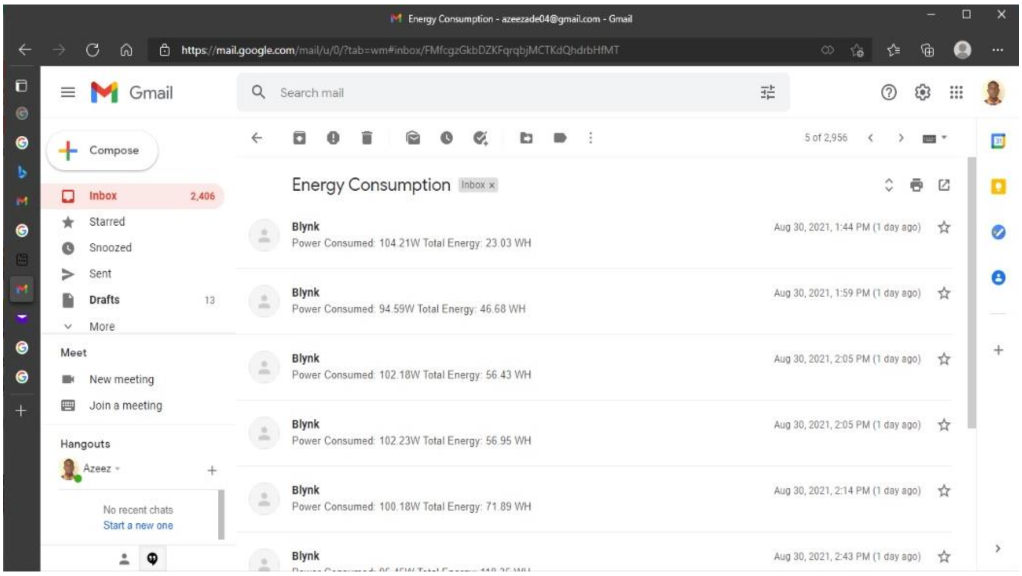


Figure 10. Sent email notifications from the Blynk application during testing

5. CONCLUSION

A robust and technologically advanced metering system that can efficiently assist the Utility in tracking the consumers' energy consumption record and subsequent bill processing is a major requirement in today's electricity business operation. This work designed, implemented, and tested a web-based single-phase load monitoring and auditing system. The test result showed that the system successfully displayed the load profile (current, voltage, power, and energy readings) on the LCD and the Blynk interface, stored the load data on the database, and sent continuous email notifications to the users on their energy consumption. The developed system is economical and has a low power requirement. It has a capacity of about 2000 W and could be deployed for residential, commercial, and other similar applications where energy consumption monitoring of small loads is desired. Further work is ongoing to improve the operational features of the developed system by integrating an automatic power shut-off unit that can protect against surges.

ACKNOWLEDGEMENTS

The authors appreciate HIC MikroLAB, Asero-Abeokuta, Ogun State, Nigeria for the immense support during the implementation stage of the developed system.

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