Development and Implementation of Energy Consumer Metering System with the Integration of Smart Users' Management Model

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Received: 06-MAR-2023; Reviewed: 12-JULY-2023; Accepted: 03-AUG-2023
http://doi.org/10.46792/fuoyejet.v8i3.1013

ORIGINAL RESEARCH

Abstract- An electrical meter with the integration of the Internet of Things (IoT) device measures and records the consumption of electrical energy in residential and commercial buildings. This allows for remote monitoring and management of the energy usage through an IoT platform. This IoT meters emerged due to the inability of the existing metering system to smartly integrate the IoT application into the metering market. With the emergence of IoT technology, microcontrollers and sensors are deployed for this model to avert the aforementioned challenges. The microcontroller is responsible for collecting and processing data from the meter, as well as communicating with the other components of the device. The communication module enables the meter to connect to the Internet and transmit data to the cloud, to be accessed and analysed through an IoT platform. The voltage and current sensors give input current and voltage signal for the microcontroller for analogue to digital conversion (ADC) effect as programmed. The experimental results indicate that the meter is accurate in measuring energy consumption with a maximum relative error of -6.06% as observed in Case 3 with a rated power of 40W and absolute current of 0.02A. The negative value of the relative error suggest that the measured energy is slightly lower than the actual energy consumed. The developed meter prototype engendered smart energy measurement with modern IoT technologies, this enables remote monitoring and of energy usage.

Keywords- Meter, Energy Management, Internet of Things, Smart Users Model, Sensors.

1 INTRODUCTION

An electric meter, often known as a kilowatt-hour meter, is a device that measures how much electricity a home, a business, or an electrically powered product uses. The meter calculates the overall amount of energy used over a period of time. Electric meter data is commonly utilized for system planning, operation management, and customer billing (Dike et al., 2017; Ugonna et al., 2018). Smart metering devices are more modern than electronic meters, and because they have a two-way communication system, they could be utilized to prevent energy theft as well as achieve remote monitoring and control. Smart meters are an alternate solution to solving the problem of energy theft and wastage in the distribution network, which is the ultimate goal of energy management (Akpan et al., 2019; Makanjuola et al., 2015). Smart meters also offer excellent metering accuracy and minimized power outages as additional benefits. The world is shifting toward automatic wireless technologies that not only reduce human work but also aid in the automation and efficiency of systems. Because of its importance in electrical energy management and conservation for both consumers and providers, the smart and automated meter is a source of concern. Electrical energy users, such as householders and industries, are only aware of their energy consumption when they go to the meter house to take physical readings or when they receive an electrical bill from suppliers (distribution companies).

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Section B- ELECTRICAL/COMPUTER ENGINEERING & RELATED SCIENCES
Can be cited as:
Usman, U. A., Ameh, M. O., Olatomiwa, L., & Jack, K. E. (2023). Development and Implementation of Energy Consumer Metering System with the Integration of Smart Users' Management Model. FUOYE Journal of Engineering and Technology (FUOYEJET), 8(3), 278-283. http://doi.org/10.46792/fuoyejet.v8i3.1013

Smart meter technology has advanced at a breakneck pace, and there is a growing demand for a dependable and efficient electrical energy consumption system. How accurate and dependable are these smart meters at measuring the amount of electricity consumed is the question in the mind of potential users. The difference between the electrical energy consumed and the projected energy consumed by the same load is used to determine the accuracy of a smart meter. Smart meter dependability can also be assessed by measuring the bit error rate of the communication network under specified noise circumstances produced by external factors such as temperature and pressure (Sabake, 2017).

Smart and digital electrical meters, which are currently used by domestic and industrial users, have eliminated some of the issues that existed with analogue and electromechanical meters in the past, which allowed users to bill and track energy usage by consumers through physical inspection. However, the idea of invention, engineering, and technology provides the potentials for innovation or modification of various instruments for ease of use and accessibility is required. This study focuses on constructing an Internet of Things electric meter and evaluating its accuracy in terms of electrical energy consumption measurement over time, as well as comparing it to existing smart meters and termed enhancement. Due to its wireless connection, the designed meter is tested for reliability and the meters are connected to an electrical load that uses energy to ensure accuracy.

Some of the related work on smart metering are discussed. In a study design of smart meter-based security systems using GSM technology (Mahale & Bansa, 2015), the author focused on the smart meter's security in

India, were the temperature in power plants, substations, and energy transmission and distribution networks was reported in this study for easier management. A thermistor connected to a microcontroller was used to measure the temperature. Because it omits electrical control, this approach is not based on energy management.

Arduino Mega and IOT-based intelligent meter (IEM) to improve efficiency and accuracy in current billing methodology, was proposed in (Jaiswal & Chaubisa, 2017). The purpose of this work is to offer a wireless technique for reading and billing Intelligent Meters (IEMs) using an Arduino Mega and Ethernet Shield. The produced bill is transmitted to the user by SMS using GSM 900, and power are disconnected for unpaid customers using relays to controlled using the Internet of Things concept (IoT). This system's strengths include speedy processing and the usage of the GSM system, which allows users to receive timely notifications via text message. Database management, on the other hand, was complicated and, therefore, classified as a complex system.

Ashna (2017) presented the design and implementation of a GSM-based remote meter operating system that addresses power theft, consumption control, auto billing and payment, data logging, and manpower reduction in power distribution and administration. The major disadvantage of the current systems was the postpaid-based services, which means that the electricity board provides service before collecting payment from customers. It was difficult for the electricity board to collect the payable amount from customers while also providing service. As a result, following payment, a system service is required.

Chore et al. (2018) offered an overview of a smart electricity system that uses an ARM-7 microcontroller to control electricity usage on the consumer side to reduce power waste. The designed system in this study evaluates power usage using an Infra ray (IR) sensor unit. The Advanced RISC Machines (ARM) processor detects the unit pulse and converts it to tariff values, which are then shown on the LCD screen for each user. When a customer fails to pay his account on time, relay mechanism is utilized to shut down or disconnect the meter and load through the supply mains. The payment of bills by users are indicated via a buzzer and light emitting diode (LEDs).

An Internet of things-based Smart Metering was designed and implemented in (Yaghmaee & Hejazi, 2018). The system measures power usage and power line parameters and communicate them to a central server on the internet via an intermediate gateway. The system has the ability to control electrical appliances and, if necessary, switch them off during peak hours and on during non-peak hours. The technology also attempted to reduce the cost of electricity for customers as well as the amount of demand on the electricity grid during peak hours. The system was created with a microcontroller unit (MCU) and a Wi-Fi module, which serves as the system's sensing unit and relays information to users via a web browser.

Ipinnimo & Yinka-banjo, 2021 addressed inconsistencies in data readings between energy suppliers and consumers by developing a mobile web application with IOT and SMS technology. It provides a user-friendly interface for consumers to monitor energy consumption in real-time, remotely turn the meter on/off, and retrieve stored data.

The existing metering system lack the ability to smartly integrating IoT applications, monitor and control electrical loads. Therefore, this work aims to address these issues by incorporating microcontroller, communication modules, and sensors (current and voltage sensor) to IoT. The use of ESP32 microcontroller allow for better control and monitoring of energy consumption, as it can collect and analyse data from current and voltage sensors and communicate it to the IoT platform (Firebase database) for remote access.

2 Research Methodology

In this study, the hardware and software components of the design of an Internet of Things-based electric meter is divided into two categories. The entire physical makeup of the design prototype is included in the hardware portion of the device. The programs are uploaded into the processing component of the design to make up the software portion of the design and the software simplifies how the entire device works.

2.1 The Hardware Component

The device's hardware is broken down into useful, functional pieces. Following is a list of the subunits: power unit, sensor unit, processing unit, display unit, audio unit, and protection unit. The sensing unit (voltage and current sensor) and the processing unit (ESP-32 microcontroller) are both powered by the power unit. Both the current sensor and the voltage sensor are powered by a 230-volt AC supply. The microcontroller receives 5V DC supply from the rectification circuit. The sensing unit's voltage and current sensors send an input signal to the ESP32 microcontroller, which processes it in accordance with specially created instructions necessary for the microcontroller to work. The microcontroller is regarded as the system's brain and heart and in addition to processing the voltage and current signal collected from the sensing unit and sending the output to the LCD display and buzzer, it also uploads the data to the cloud to be accessed via a mobile app that has been downloaded on a smartphone. The mobile app also shows the related current, voltage, and total energy consumption in kWh, these are evaluated from any location in the world using the internet.

The LCD display also shows the current, voltage, and total energy used in kilowatt-hours when the mobile application is inaccessible for a given period of time. When the system is in used the audio unit (buzzer) serves the purpose of giving an audio signal to the user to show that the system is operational. The switching component (relay) serves as a protective mechanism for the load in the event of a temporary fault. The block diagram in figure 1 explains how the hardware parts are connected to one another.

http://doi.org/10.46792/fuoyejet.v8i3.1013 journal.engineering.fuoye.edu.ng/

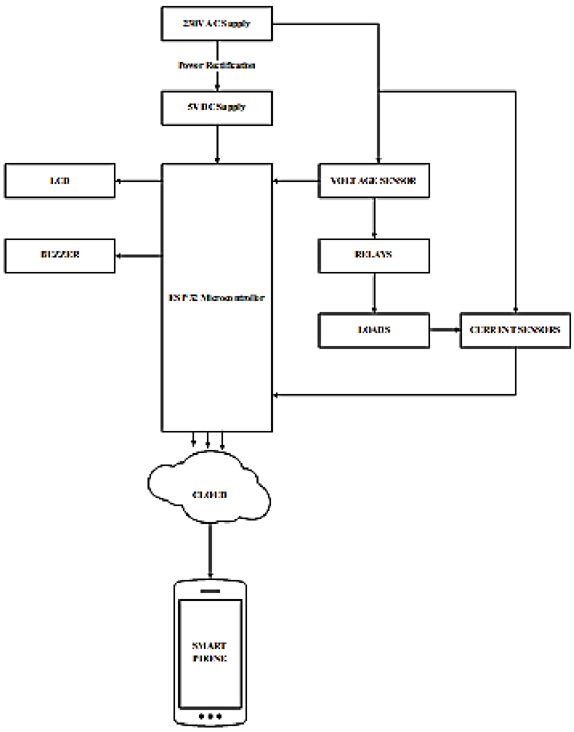

Fig 1: Block Diagram of IoT-based Meter

2.2 The Software Component

The system's software components are a collection of operational guidelines and applications used to control the hardware element of the design and carry out the desired task. Three functional elements make up this component: Android application software, the Arduino IDE programming environment, and the Proteus simulation software. The Android app is a piece of software with a graphical user interface that enables users to communicate with the meter, monitor, and control the load. This mobile application with a graphical user interface was produced using MIT Lab Innovator. The programming tool (Arduino IDE) was used to create the codes that provide instructions for the microcontroller's operation. The circuit of the proposed meter was simulated using the Proteus simulation software to determine the workability of the system.

2.3 The Proposed Algorithm

At the beginning of the system processing, the hardware settings (Wi-Fi, LCD) are initialized, a startup message was displayed on the LCD, analogue to digital conversion was done by the current sensor, and if the conversion cycle are completed, the microcontroller computes the current (A), power (kW), and energy consumed (kWh) and sends the output to the display unit (LCD) and online server to be accessed by the deployed mobile app. However, if the conversion cycle is not completed, the process initializes again. This whole process is as illustrated in figure 2.

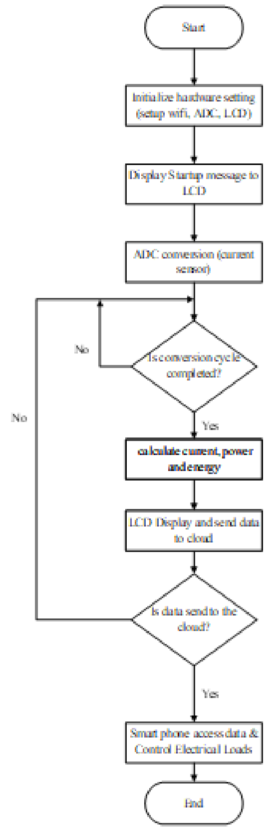

Fig 2: Flowchart of the proposed IoT-based Meter

2.4 Mathematical Model of the Energy Meter

First, according to Ohm's law, the resistance (R) of a conductor serves as the constant of proportionality between the current (I) flowing through it and the voltage (v) applied across it. Mathematical representation of this relationship is as follows:

$$I = \frac{V}{R} \tag{1}$$

Next, the power factor measures how effectively the current are being used by the d and the ratio of the real power (P) being consumed by the device to the apparent power (S) being supplied to it. This relationship is expressed mathematically as

$$PF = \frac{P}{S} \tag{2}$$

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The power equation is used to calculate the amount of power being consumed by the device and power (P) equal to the product of the voltage (V) and the current (I) flowing through the conductor, multiplied by the power factor (PF). This relationship is expressed as:

$$P = V \times I \times PF \quad (3)$$

By combining these equations, mathematical model is created and are used to calculate the amount of electrical power being consumed by a device using the voltage, current, and power factor measurements taken by an electric meter. The mathematical equation for the energy consumed by a load depends on the type of load and the way in which it consumes energy. The amount of energy consumed by a load is equal to the product of the power consumed and the time for which the load is powered.

$$Energy\ (E) = P \times t \quad (4)$$

where P is the power consumed by the load in watts, and t is the time for which the load is powered in hours. Also,

$$Energy\ (E) = IVt \quad (5)$$

In some cases, the load may consume power at a variable rate, in which case the energy consumed by the load are calculated by integrating the power consumed by the load over the time period for which it is powered and represented by:

$$E = \int_0^{t_n} P(t)dt \qquad 0 \le t \le t_n \quad (6)$$

The total power consumed over time t for n loads is given as

$$E_T = E_1 + E_2 + E_3 + \cdots E_n \quad (7)$$
$$E_T = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n}(E_1 + E_2 + E_3 + \cdots E_n) \quad (8)$$
$$= \sum_{i=1}^{n}(P_1 t_1 + P_2 t_2 + P_3 t_3 + \cdots P_n t_n) \quad (9)$$

Generally, the exact mathematical equation for the energy consumed by a load depends on the specific characteristics of the load and the way in which it consumes power.

2.5 The Metering Prototype

The metering prototype was developed through simulation and design implementation. Simulation was conducted using Proteus software, and provided a clear picture of the arrangement of rated components to arrive at a fully functional model. The simulation was carried out on the different modules individually and on the system as a whole. The simulation helped in identifying the exact components as well as their rating and arrangement to be used to arrive at this fully functional model. The resulting circuit diagram of the final simulation is shown in figure.3. The components were patched according to the circuit diagram on a bread board to obtain the first physical prototype of metering system. The metering communications module were arranged on Vero board as shown in figure 4 to allow work diagram on a breadboard to allow for flexibility, especially in packaging.

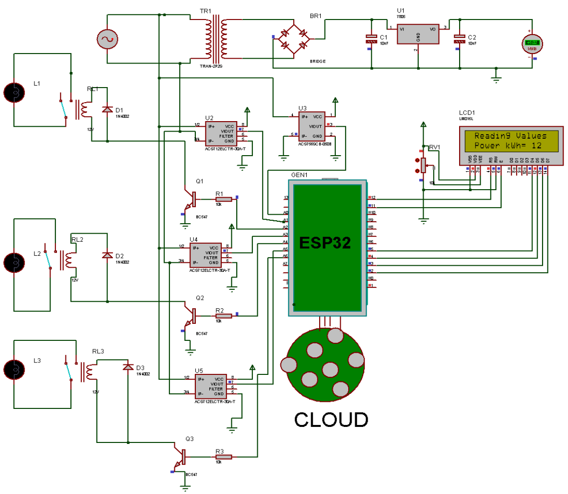

Fig 3: Circuit Diagram of IoT-based Meter

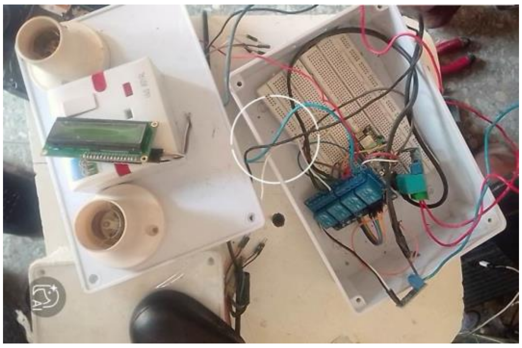

Fig. 4: Bread Board Model of the entire system Module

3 Experimental Results and Discussion

3.1 Testing

A number of tests were conducted and each of the meter modules were first tested individually to verify their functionality. The modules were then assembled together and tested as a complete unit. A number of loads with different power rating as given in Table 1 were used. For Experimental studies, loads are connected in different combinations as given in Table 2, the readings were recorded and crosschecked against the real time data sent to the cloud (firebase) which is accessible on a mobile phone.

Table 1. Capacity of loads

Loads	Power rating	Rated current
Load 1 (Filament Bulb)	100W	0.43 A
Load 2 (Filament Bulb)	60W	0.26 A
Load 3 (Electric Fan)	40W	0.17 A

Table 2. Different type of Load Combinations

Cases	Description
1	Load 1
2	Load 2
3	Load 3
4	Load 1 + load 2
5	Load 1 + load 3
6	Load 2 + load 3
7	Load 1 + load 2 + load 3

Figure 5 shows the complete assembly of the system, while Figure 6 depict the link between the Android application and the load to be monitored and controlled. The application was installed on a Techno WX3 Android phone and initialized. After initialization and connection between the meter and Android phone was established, the real-time current and energy consumed by loads were also displayed on the phone accordingly. The controlling mechanism of loads was done remotely from the Android application which triggered the relay to trip either close or open by clicking the buttons which was immediately followed by the lighting of the bulbs and socket outlet connected as load. The process was carried out a number of times to ensure the process was functioning properly.

Fig. 5: Complete Assembly of the system

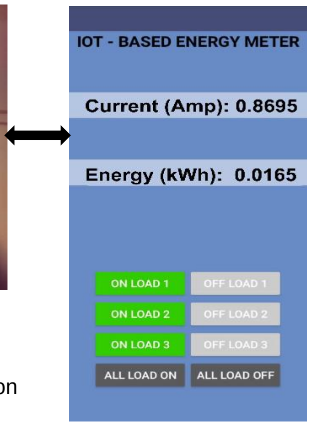

Fig 6: The Android application Interface and the Load

3.2 Experimental Result

The meter was tested for accuracy in measurement and ability to transfer real-time data to database. A rated voltage of 230V and frequency of 50Hz was recorded during the experimental setup. To validate the readings against theoretical estimates, the energy consumed (E) is calculated as the product of power (P) and time (t) for an interval of 5 minutes (300 seconds) using Eqn. (4). This theoretical estimation is compared with the measured energy consumed by loads as displayed by the developed meter. The relative error (%) is then calculated to determine the accuracy of the IoT-based meter. The corresponding values of load study is given in Table 3.

3.3 Discussion Of Result

The experimental result presented shows the performance of an energy meter developed to measure energy consumption under different input parameters. The meter was tested in various cases with different rated power, actual energy consumed, and measured energy consumed.

The results indicate that the developed meter has good accuracy in measuring energy consumption with a maximum relative error of -6.06%. The negative value of the relative error suggests that the measured energy consumed is slightly lower than the actual energy consumed. The highest relative error is observed in Case 3 with a rated power of 40 W and an absolute current of 0.02 A, while the lowest relative error is in Case 5 with a rated power of 140 W and an absolute current of 0.02 A. The actual energy consumed ranges from 0.0033 kWh to 0.0167 kWh. The experimental results suggest that the developed meter has good accuracy in measuring energy consumption.

Table 3. Energy consumption measurement, accuracy result of the developed Meter

Case	Voltage (v)	Rated Current (A)	Measured Current (A)	Absolute current (A)	Rated Power (W)	Actual Energy Consumed (kWh)	Measured Energy Consumed (kWh)	Relative Error (%)
1	230	0.43	0.41	0.02	100	0.0083	0.0082	-1.2048
2	230	0.24	0.21	0.03	60	0.0050	0.0049	-2.0000
3	230	0.17	0.19	0.02	40	0.0033	0.0031	-6.0606
4	230	0.69	0.62	0.07	160	0.0133	0.0130	-2.2556
5	230	0.61	0.63	0.02	140	0.0117	0.0116	-0.8547
6	230	0.43	0.39	0.04	100	0.0083	0.0081	-2.4096
7	230	0.87	0.86	0.01	200	0.0167	0.0165	-1.1976

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4 Conclusion

The development and implementation of Energy consumers metering system with the integration of smart users' management model was a major breakthrough in the field of energy monitoring and management. With the ability to send real-time current and energy consumed in kWh to online database, users can access information about their energy consumption and control their appliances from anywhere in the world through a mobile application at their convenient time.

Experimental result indicates that the meter is accurate in measuring energy consumed. This design offers a lot of benefits, including the ability to accurately monitor energy consumption, identify patterns in energy usage, and make informed decisions about energy conservation. It also allows users to set alerts and notifications to help them stay within their energy consumption targets.

Furthermore, the integration of the ESP32 development board with the online database and mobile application enables seamless and efficient data transfer, making it easier for users to access and manage their energy consumption information. With the increasing focus on energy efficiency and conservation, the implementation of this electric meter provides a valuable solution to help individuals and organizations reduce their energy consumption and ultimately contribute to a more sustainable future.

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