

Original Research Paper

Design and Construction of a Smart Meter with Embedded Web Portal

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Abstract: The absence of the necessary infrastructure to make an accurate and precise collection of data when compared to the first-world countries in the power industry is great. Due to that, the need for the deployment of smart meters has increased in order to offer consumers and customers awareness of their electricity usage, helping them lower their total energy footprint. In this study, real-time low-cost energy management is designed and developed with an embedded web server integration. Using both real and reactive power data obtained from the smart energy system, the power quality can be made better for people taking their power straight from the grid. The work drives building a smart metering solution that helps in the process of monitoring. This smart metering solution involves connecting a load displacement sensor, which is an example of a smart sensor, to a web server, which tracks power consumption. It is mainly utilized for managing the overall power plant and measuring the major power system quantities. Data compression is employed for measurements of power quality and for speeding up the process of data loss prevention. When excess electricity usage occurs, the electrical energy is disconnected from the grid. Future residences will be designed to provide a high degree of interconnectivity and scalability. We demonstrate that by utilizing the foundational ideas of modern Web architecture, we can quickly and simply construct reliable, versatile smart Meter applications with few drawbacks.

Keywords: Electrical Energy, Embedded Web Portal, Smart Meter

Introduction

Electrical energy has become a necessity for the activities man partakes in from applications in industrialization to domestic use, electrical energy powers our everyday lives. The importance is proven by the increase in electrical energy usage year after year. Taking a record of this subset of energy at the consumer end is possible with the use of energy meters for monitoring and setting tariffs for electricity consumers. So far in Nigeria, there has been a roll-out of prepaid meters, which was started by the Power Holding Company of Nigeria (PHCN) from the year 2006 to increase revenue collection in order to reduce their debt profile because consumers were defaulting

on tariffs due to the policy of post-payment, that meant that customers paid after using electricity and this caused a loss in revenue (Orukpe and Agbontaen, 2013). However, this has only had the advantage of revenue collection for the distribution company and the benefit of cost savings for the consumer. For the utility company, it was found out that the roll-out of prepaid meters increased the collection of revenue because consumers now must pay for electricity before use, however, the roll-out of prepaid meters did not increase revenue generation due to the prepaid system having a reliability dependency. Because electricity is not always available, the utility company did not get as much remuneration as they could get in the case estimated reading.

A study was carried out in Ugbowo, Benin City, Edo State where postpaid and prepaid values for consumers were collected from Jan. 15, 2007, to Jan. 15, 2008, and Feb. 3, 2007, to Jan. 21, 2008. In January 2008, for the same period, the postpaid bill for consumers was ₦36,717.60 as against ₦4,700.57 (Ogujor and Otasowie, 2010). This difference in bills to be paid in both instances clearly shows a loss of revenue due to low reliability stating the roll-out of prepaid meters did not do much for the reliability of the power grid. For metering to aid revenue for power utility companies, more data relating to customer use, power quality, and times of outage so that they can be able to accurately rate delivery performance. This data can only be collected with a smart meter.

A smart meter is an advanced energy meter that measures consumer energy consumption and relays such information to the power utility company. The major differences between a smart meter and a conventional meter are evident in the increased level of detail as more data is collected and two-way communication for both data and power (Depuru *et al.*, 2011; Franek *et al.*, 2013). This means that energy consumed is seen by the consumer and the utility company, the connection to the utility company means they can collect the data needed for them to improve power generation, transmission, and distribution efficiency as well as increase the feasibility of flexible tariffs due to the efficiency as utility companies know how much power is used against how much is generated. Power stations can monitor power consumption more closely and can adapt to demand and supply faster, thus, reducing blackouts and power overproduction, which can lead to power wastage. On the other hand, consumers can see data in higher resolutions than before, enabling them to make better choices relating to their power usage, adding up to potential cost savings.

The potential for cost and energy savings with the use of smart meters presents a solution for low-energy production in Africa. Using Automated Meter Reading (AMR), an intelligent distribution system can be realized (Popa, 2011). Thus, the energy already produced can be used for even more homes as less energy is wasted, resulting in more people having electricity.

The lack of infrastructure to make accurate and precise data collection possible as compared to first-world countries as it relates to our power industries is massive; this shows we are leaving a lot of potential untapped. For improved quality and growth in and size of our power infrastructure, data collection is of the utmost importance. Using real and reactive power data obtained from smart energy systems, power quality can be improved for people who take their power straight from the grid. As a monitoring tool, it also brings a convenient solution for

people using renewable energy solutions as they can track the energy usage of their homes.

This study aims to build a smart meter and a web portal for energy monitoring, thereby enabling consumers to monitor the energy consumption patterns in their buildings from any location, thereby mitigating against energy theft. The objectives of this study are: To build a networked smart meter that will be used to monitor electricity usage; to code the Arduino C software which will be used to configure the microcontroller to communicate with the GSM module and current sensor; Testing of the accuracy of the smart meter system; deployment of the smart meter system for power usage monitoring. The basic process adopted for the actualization of the aim of this study is outlined: The hardware of the networked smart meter is built, with the components mounted on a Vero board and soldered to the surface. Tests are run to ensure all the components are working properly; next, the software program of the microcontroller is written using the Arduino integrated development environment. The software program for the Arduino will be written in C++ language; various tests are carried out such as an initial power-on test, instrumentation test, and web platform test to ensure the work meets the requirements of the research; Lastly, the networked smart meter is deployed for on-site power usage monitoring.

An energy meter is a device that monitors how much electrical energy is consumed by a residence, company, or electrically powered device. They are normally calibrated in billing units, the most common of which is the Kilowatt-hour (KWh). The invention of the transformer made an electric meter that finds its application in alternating current a huge necessity. With a prepaid energy meter, utilities can collect electricity payments in advance from customers. Prepayment makes the consumers conscious of energy wastage because the user is automatically disconnected when the payment plan is exhausted. Prepaid meters are usually used in developing, politically unstable, and underdeveloped countries (Garcia *et al.*, 2017). Utility companies spend less money since energy workers will no longer visit consumers to get energy meter readings. Due to the high demand for electricity and the need for energy management, smart meters have been developed to improve energy efficiency both for consumers and energy providers. This type of energy meter called a smart meter, measures the amount of energy used by a customer and provides the utility company with that data as well as other information they may need. Because of this, the traditional and antiquated method of manually reading the amount of energy used is no longer applicable to this new technology (Arif *et al.*, 2013). Smart meters were first used for billing commercial and industrial consumers whose billing rates

were more sophisticated. Over time, as the cost of technology required for the implementation of smart meters and the need for advanced billing requirements for all classes of consumers, migration to smart meters has become more rapid.

Zaidi *et al.* (2008) designed a low-cost electronic prepaid meter that meets the demands of the poor and middle-class citizens of Pakistan. The emphasis of the research was on cost and reliability and a quick replacement for the electro-mechanical meters. ICs and microcontrollers were used in their design and they are reliable because of the absence of moving parts that could easily cause wear and tear. The energy readings are displayed to customers on an LCD. A smart card system is also designed to cut the cost of meter reading and the project is based on both the metering and billing system.

Pre-paid energy meters that can be connected to a central hub have been developed (Ramadan *et al.*, 2013). If the meters are linked together, it will be easier to control and maintain them in the future.

The network is cost-effective due to its utilization of existing power lines rather than the purchase and installation of new wired or wireless network infrastructure. Power line Communication (PLC) technology is used to send the data across this network. The power line communication modem is used to transmit and receive data over a network using a particular equipment. The network is structured in such a way that the energy provider may access and control the measurements of every prepaid energy meter in the unified region, preventing electricity theft. If the corporation sends text messages to consumers, such as a serial number or an alert before all of the electricity is utilized, it can connect with them. Additionally, this network allows users to control the flow of energy by turning the supply on or off. Ramadan *et al.* (2013) created a prepaid energy meter that was connected to the utility. They sent data between occupants and energy companies via PLC technology.

Using the International Standard, the single-phase prepayment kWh meter is made up of energy metering and the S.T.S. system: IEC 62055-31, 62055-41, and IEC 62055-51. The energy meter measures voltage and current on the line and calculates active, reactive, and apparent power, energy, and power factor, as well as R.M.S. voltage and current. Hindersah *et al.* (2011) used two separate inputs to measure line ground and/or neutral current, enabling the meter to detect tampering and to continue operating. Single-phase development is based on the needs of P.L.N., which is approximately 7 million units of kWh meters through 2014, particularly for new consumers. The prototype of a single-phase prepaid kWh meter was constructed using the Cirrus logic CS5464 integrated circuit, which is widely used in energy metering subsystems throughout the world, and the Texas

instruments MSP430™ series, which has an ultra-low power consumption for the S.T.S. subsystem.

Teymourzadeh *et al.* (2013) proposed the use of RFID technology in prepaid energy meters. RFID cards contain energy-related data. To replenish the energy, this RFID card is connected directly to the computer via the MAX232 IC. Providing electric energy service requires the use of an electrical power meter. Many customers have already expressed their dissatisfaction with the accuracy of their electric meter readings. This study examines the creation of a power meter with an RFID reader. A genuine RFID tag is picked up by the RFID reader. Using the RFID card, the power meter is activated and ready to provide power. An SMS message will be delivered to the user's mobile phone when the credit is about to run low or before the energy is automatically shut off. The RFID power meter's operation based on credit top-up is successful, according to the results of the trial. Users will be able to better manage how they utilize electric energy as a result of this. Additionally, the RFID power meter will send an alarm to the user's mobile phone when the credit is running low. When the credit is used, the electrical supply will be automatically shut off.

Wan *et al.* (2014) suggested a wireless prepaid energy meter technology. The system was controlled via smart agents. Due to the advent of the Pre-paid Meter (PM), utility companies are no longer required to visit homes to read meters, which may be a time-consuming and difficult task. To create a wireless smart power meter, a proposal and prototype were created using smart agent technologies on the Android Jelly Bean mobile platform using the Eclipse IDE. By eliminating the need for any human intervention, the system was able to move and query energy units in real time. In the future, agents from consumers' mobile devices will be able to query the energy meter to learn how much power they use and how much they need to replenish.

Mohammad *et al.* (2013) developed a smart prepaid energy meter solution to combat electricity theft using an ATmega32. Power companies in several countries, particularly in poor countries are suffering enormous losses as a result of electricity theft. Mohammad *et al.* (2013), every consumer unit is equipped with a smart energy meter and the service provider maintains a server. To permit bidirectional communication between the two ends, the meter and the server are both outfitted with GSM modules. Recharging an energy meter is as simple as transmitting a PIN number from a scratch card to the server through SMS, which is hidden on the card. Measures to prevent meter bypassing and tampering are discussed in this study. The efficiency of these procedures is ensured by bidirectional GSM communication through SMS. When combined with prepayment metering, the recommended solutions can significantly reduce electricity pilferage. While the

GSM network supports the concept of prepaid electricity use, it also aids utilities in combating energy theft through the implementation of smart energy meters. The central authority receives information on electricity theft straight from this mechanism. Because of this, utilities can initiate legal action against an accused customer right away, helping them keep a tight rein on electricity theft. Power utilities will greatly benefit from the new meter because it will help cut down on electricity theft and help collect revenue.

A system was proposed Perekalskiy and Kokin (2020) that works with the Internet for collecting data. This means that utilities can collect information with a connection to a meter or a connection between meters to collect precise data needed for billing customers and other power system functions like load forecasting and balancing, and load shedding applications are also present with this network infrastructure. The channels for this form of communication can be initiated with GSM or a Wireless Fidelity (Wi-Fi) Network. The system architecture of this smart meter is based on a microcontroller which is the ESP8266 (Perekalskiy and Kokin, 2020) as the center of the system used as a processing hub for signals transmitted by the sensors and communication devices to different parts of the system enabling each part to serve predefined purposes. Parts of this system include metering blocks, power supply, GSM module, relays, LCD, and Load. This system tests the concept of reliability in sending meter readings with the implementation of both Wi-Fi and GSM networks. The consumption data and daily behavior patterns of several households were studied and graphed in this thesis.

Energy meters that track the use of electricity for revenue generation have been developed. The design of this meter faced the challenge of eliciting the functional requirements as cost and functionality is being considered. The design of the SEM included the current sensor, power unit, memory microcontroller, communication module, a component for energy measurement, and a voltage sensor. An Arduino UNO was the main microcontroller, a half-wave bridge rectifier circuit to detect AC voltage, an ACS712 20A current sensor to measure AC, a GSM modem to link the meter to the customer, and a relay to remotely switch the loads on and off. A voltage sensor, a current sensor monitors voltage and current levels and sends those data to the microcontroller (Arduino). The GSM module is utilized to establish a communication link between the customer and the meter. That is, data from the microcontroller chip is sent to the GSM module, and data is then transmitted to the user from the GSM module.

Whether a residential load, commercial load, or industrial load is linked to a smart meter, it can enable the monitoring of electrical supply as well as safeguarding the

loads from over- and under-voltage. The off-peak loading concept is further supported by the fact that it may be implemented in real time. It also helps customers save on their energy expenses and extends the equipment's life while still being easy to operate (Reddy *et al.*, 2019). Monitoring of variables relating to the control of essential systems and services that have a cost to run is a need of a smart city. Power is also an essential service as smart grids are the backbones of smart cities, without power everything fails. The smart meter in Hasan and Kadhim (2020) performs some operations and has extensive communication capabilities needed because the system must give data accurately and on time, that characteristic also extends to the control functions, which greatly affect factors like safety. This metering system consists of multiple smart meter nodes and a data center represented by a small computer called a Raspberry Pi (Hasan and Kadhim, 2020). The network is centralized as the Raspberry Pi receives packets from all the meter nodes through Message Queuing Telemetry Transport (MQTT) protocol, this communication feature put in place also facilitates sending data for monitoring and can be disconnected remotely. Cost estimation is also considered with the system as a digital setup allows flexibility with tariffs. Islam *et al.* (2012) monitored an electronic energy meter using an ATmega8L. Numerous researchers have included an ATmega in their system as a microcontroller.

Meters can be subjected to data falsification of energy usage (Baskaran *et al.*, 2021). Attacks can be in the form of additive, causing loss to consumers, or deductive, causing loss to utility companies. The integration of an embedded web portal which is proposed in this study will mitigate the effects of these attacks as historical data indicating consumption behaviour is being monitored and stored (Dahunsi *et al.*, 2021). Therefore, any change, falsification, or energy theft (Zulu and Dzobo, 2021) can be deciphered. The design of this study will facilitate automatic monitoring, recording, and billing (Chai and Lee, 2021; Muhamad *et al.*, 2022) of energy consumption in buildings.

The review conducted gives a better understanding of smart meter design over the years. The works reviewed, therefore, help in enhancing the design and implementation of this study with another approach.

Materials and Methods

In this section, the method for designing and constructing the smart meter with an embedded web portal is discussed. The section starts with the design of the embedded smart meter consisting of the hardware components (power supply unit, microcontroller, and AC communication module) and software design. Issues relating to design specifications will be addressed with details of the steps involved in the processes.

System Design and Implementation

Table 1 and Fig. 1 give a breakdown of the major components of the networked smart meter build. The hi-link intelligent supply module sends power supply through the ESP-12E Wi-Fi communication module. This module transforms the voltage into direct current for use by the smart meter. With the use of a switch mode supply the mains power is regulated. The communication signal is then sent to the AC communication module, which is then used to operate the microcontroller and give a displayed output on the LCD.

Hardware Design

This section discusses the hardware side of the networked smart meter.

Power Supply Unit

A unit for supplying power is essential in this study as it provides the electricity needed for the components of the Smart Meter. The power supply unit includes a rectifier, chopper, and filter unit (Manias, 2017). Figure 2 illustrates how the 230V-AC mains supply is transformed to 5Volts in DC with the use of the power supply module. A Switched Mode Power Supply (SMPS) is being used to regulate the mains power supply for the smart meter.

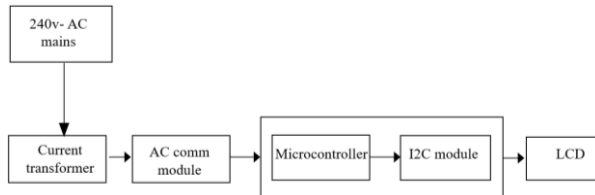


Fig. 1: Overview of a networked smart meter

Table 1: The major components of the networked smart meter build

No.	Unit	Component	Specification
1	Power supply	Hi-link intelligent supply module	Input voltage range = 100v-240v-AC Output Voltage = 5v-DC Operating frequency = 50-60 Hz Current rating = 600 mA
2	Control	ESP8266MCU	Input voltage: 5v-DC
3	Communication	ESP-12E WIFI Module	Operating voltage = (3.0-3.6) v-DC Frequency range = 2.412 - 2.484 GHz Baud rate = 9600bps
4	Load	Variable	Operating voltage: 240V AC Operating frequency: 50Hz Power rating: up to 3KW
5	Sensing	Current sensor and current transformer	Primary current: 5A nominal, 100A maximum Operating frequency: 50Hz Turns ratio: 100:1 nominal Volt per Amp ratio at 5A: 1 V/A
5b	Sensing	AC Communication module	Measuring range (voltage) = 80-260V, (Current) = 0-100A Accuracy / Tolerance = 0.5% Baud Rate = 9600bps
6	Software	Arduino IDE, HTML, windows OS	C++ ISO/IEC 14882:2011
7	Display	LCD	

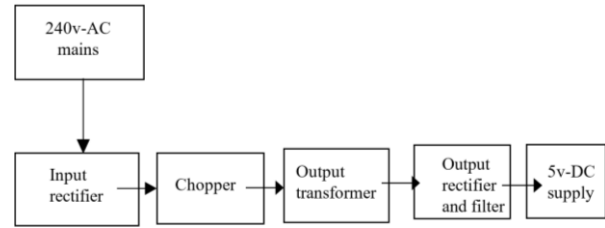


Fig. 2: Networked smart meter component layout

The system is powered by a power supply unit that supplies 5v DC to the whole system which includes a microcontroller and AC communication module. The hi-link intelligent power supply module was selected for this study (Hi-Link, 2014). This module is built with features such as stable regulated output, short circuit protection, overload shutdown, over-voltage protection, wide input voltage range, 100-240v AC, operating frequency: 50-60Hz, a maximum current rating of 0.6A, modular and miniaturized size. The choice of this power supply comes with the need to make the networked smart meter portable as building an entire housing for a power supply by traditional means is not feasible if practicality is being considered.

Microcontroller (ESP8266MCU)

Wireless internet access can be introduced to any microcontroller-based device with simple connectivity (SPI/SDIO or I2C/UART interface) by acting as a Wi-Fi adaptor. The NodeMCU ESP8266 development board includes the ESP-12E module, which contains the ESP8266 chip, which is powered by a Tensilica xtensa 32-bit LX106 RISC CPU. The Real-Time Operating System (RTOS) supported by this microprocessor is useful for real-time data monitoring and gathering and runs at a configurable clock frequency of 80MHz to 160MHz. When it comes to memory, node MCU has 128 KB of onboard RAM and 4MB of flash memory to work with. Low power consumption, in-built Wi-Fi / Bluetooth, as well as deep sleep operating characteristics, make it an excellent choice for Internet of Things projects of any size (IoT).

AC Communication Module

Using this module, the AC voltage, AC current, power factor, active energy, and frequency can be monitored. Using the AMTmega 328p chip and the Arduino mini's Transistor-Transistor Logic (TTL) Interface, data will be read. A built-in shunt resistor measures up to 10Amps of current, while an external transformer measures up to 100Amps of current. A 2-kilobit serial electrically erasable programmable read-only memory with more than is present on this module with more than 1 million read and write cycles enables this module to be suitable for the networked smart meter as the huge number of cycles to last for years without the chip getting unstable and data getting corrupted.

Component Layout Diagram

Figure 3 shows the circuit diagram of the smart meter with an embedded web portal.

Software Design

The Arduino Integrated Development Environment (IDE) was used to configure the microcontroller to communicate with the GSM module and the current sensor during the software design phase. Arduino IDE is an open-source software platform that is run on computers to upload the software program to the physical board. The Arduino IDE uses an efficient interpretation of C++, which makes it easier to learn the methods of programming on it.

A web server is a location where pages and web applications are stored, processed, and distributed to Web clients. In other words, a web browser (web client) is exactly what it sounds like A web browser that we use on our laptops and cell phones. Hypertext Transfer Protocol is the communication protocol between the client and the server (HTTP). The ESP8266 gives the benefit of allowing a Wi-Fi network to exist while also allowing other devices to connect to it and access the Internet directly. In station mode, ESP8266 can function as a regular Wi-Fi access point, and in soft access point mode, it can connect to another access point. However, both of these features are active at the same time.

The HTML Language is known as the basic building block of the web, which includes websites and web-related applications. It defines the structure of web content as well as its meaning. In this study, basic HTML was chosen for its simplicity and was embedded in the code with the Arduino IDE. The UML diagram for the smart meter with the embedded web server is shown in Fig. 4.

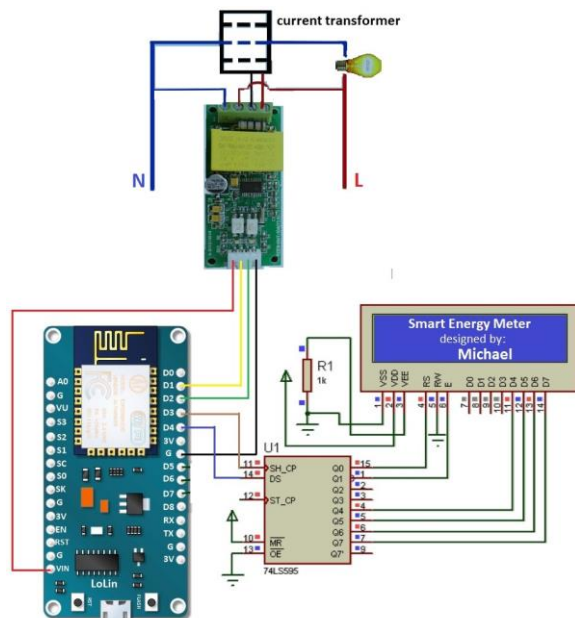


Fig. 3: Layout Diagram

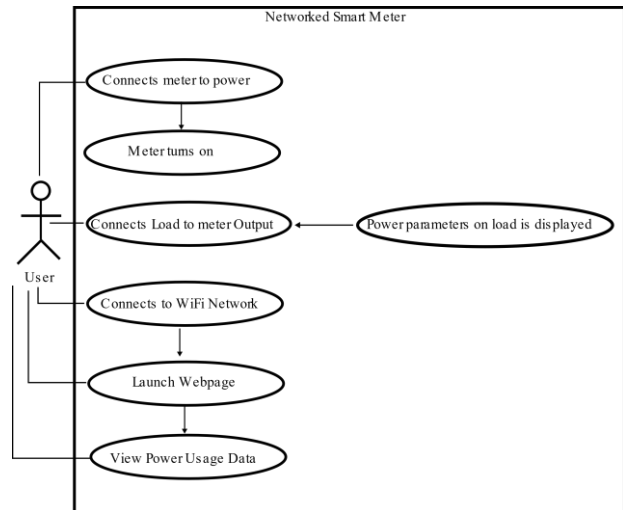


Fig. 4: UML block diagram

Results and Discussion

This section shows the implementation of this study along with the several stages of research testing involved at the different levels to ensure that the project functions as desired. The implementation stage begins with the purchase of the hardware components needed for building the project. The purchased components were coupled and the software programming for the Arduino was done. Finally, various sections of the work were tested to validate the workability of the project and to test and fix possible errors. The implementation of this study is divided into both hardware and software Implementation.

The software implementation phase involved the software programming of the microcontroller using the Arduino Integrated Development Environment (IDE) which was installed on a personal computer running on the Microsoft Windows 10 operating system. The software program for the Arduino was written in C++ language. After writing the program it was compiled and run to check for bugs and then it was uploaded onto the microcontroller using its micro-USB port.

The hardware implementation phase involves The building of the circuit on a breadboard, final implementation on a Vero PCB Board, and final packaging.

Patching of the Circuit on Vero PCB Board

This is a physical representation of the circuit diagram. In this stage, different components were tested and the best ones suited to the use of the work were then used.

Final Implementation on a Vero PCB Board

Once individual components have been tested to work well with each other and produce expected results with a good level of accuracy, components were mounted on the board and soldered on the surface in Fig. 5. Tests were run

to ensure all the components were working and not damaged by the heat of the soldering, upon any damage, components were replaced. It is to be noted that the process of connection and soldering was done on a stage-by-stage basis to address errors early on.

Final Packaging

An arrangement was made to give the work a compact size after which it was put in a cuboid PVC container with the LCD screwed to the top for the display. The use of the intelligent power system kept the total build and construction compact. Testing was done on the networked smart meter to ensure it meets the requirements of the aims and objectives of the work. These tests involve the initial power-on test, instrumentation tests, and web platform tests.

Initial Power on Test

The input ports are connected to a power source via a plug connected to a solid copper cable. When powered on, the screen comes on with a welcome message and then proceeds to show values for current, voltage, power, frequency, power factor, and energy in Fig. 6.

Instrumentation Tests

This covers the measurement of electrical quantities which includes voltage, current, power factor, frequency, and energy in comparison with an actual meter for test of accuracy (Fig. 7).

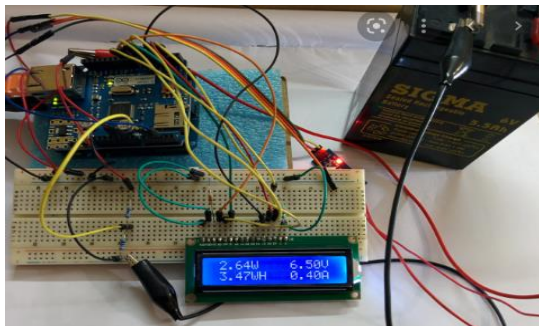


Fig. 5: Smart meter on Vero PCB board



Fig. 6: Networked smart meter power-on screen



Fig. 7: Metering comparison test

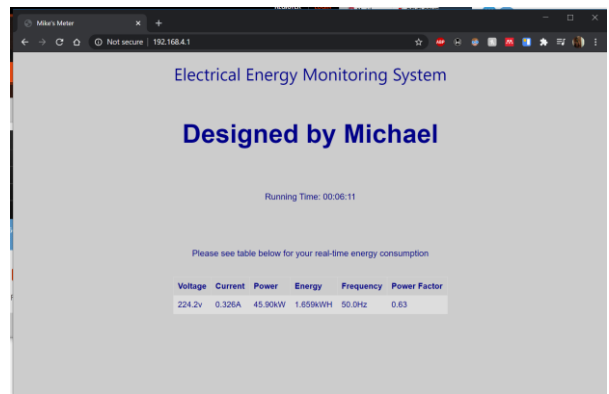


Fig. 8: Web platform test

Web Platform Test

This test confirms the remote monitoring of the smart meter is possible via connection to a Wi-Fi hotspot. With both the Station (STA) mode and the Access Point (AP) mode being active, it allows devices to connect to the web platform (Fig. 8) and access the internet directly, creating a mesh network.

Conclusion

The work aimed at creating a smart meter capable of providing real-time energy usage information to customers and utility companies, via the embedded web server. With this design and implementation. Customers can set electricity-saving goals and can be remotely disconnected from electricity by them or by the utility company. The meter can also record the frequency of blackout occurrences. With this implementation, utilities can determine how much they are losing due to poor reliability. With the implementation of this study, the following objectives were accomplished: Successful design of a system that can measure current, voltage, total power used, and power factor; Successful design of a web portal for monitoring current, voltage, and power consumption. Future work includes the implementation of an upgraded meter design to accommodate multiple

input energy sources, multiple network transmission modules to improve reliability, and an intelligent distribution network for the interconnection of multiple meters over an area or vicinity to monitor and predict energy usage for optimal grid operation, cost and energy savings. The implementation of a networked metering system will give power consumers and utilities the much-needed data and tools to evolve to create a smart power network.

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Author's Contributions

David O. Mike-Ewewie: Conceptualization, investigation, methodology, resources, software, hardware, written originally drafted preparation.

Ayodele H. Ifijeh: Investigation, methodology, project administration, supervision, validation, written reviewed, and edited.

Victoria Oguntosin: Validation, written reviewed, and edited.

Emmanuel Adetiba: Methodology, formal analysis, project administration, supervision, validation, written reviewed, and edited.

Ethics

The research presented in this manuscript involves the design and construction of a prototype. No human or animal subjects were involved in this research.

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