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Design and Implementation of a Smart Home Energy Management System

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Abstract— The exponential growth in complexity and declining cost of electrical parts has led to a proliferation of electrical appliances in the household, thus increasing the electricity demand. Increased tariffs and lapses in electricity supply by the Nigerian government and growing environmental concern has collectively influenced the need for the consumer to be able to effectively monitor and hence efficiently consume the limited energy. Existing energy management systems are relatively expensive and limited to whole house power monitoring and therefore not feasible in middle to low-income households which make up the bulk of Nigeria's population. This project aimed to measure, monitor, and analyze the energy consumption of individual electrical appliances in the home using a relatively low-cost combination of an Arduino UNO R3, ACS712 current sensor and a web application. By showing the consumers how much energy is being consumed and hence how much money is being spent on individual devices, a better understanding for the need for efficient energy consumption would be developed and implemented.

Index Terms— energy management, intelligent systems, internet of things, smart grid, smart homes

1 Introduction

Electrical energy, due to the cost of generation, transmission and distribution, is considered a commodity which is sold by either Government owned bodies or third party companies to different classes of consumers. The measure of this cost is called a tariff and is defined as the schedules or rates framed for the supply of electrical energy to different classes of consumers. The tariff usually consists of a fixed charge and a variable charge which is based on the amount of energy consumed per hour measured in kilowatt-hour (kWh) [1].

The National Electricity Regulatory Commission (NERC) instructed the scrapping of the fixed tariff charge and the increase in the variable tariff for different regions across the country. Consumers under the Eko and Ikeja electricity distribution areas who pay ₦12.87kWh and ₦13.61kWh respectively would witness a ₦10 and ₦8 increase respectively in their energy charges. This would imply that the consumer would be strictly charged based on how much energy is being consumed [2].

Also, the process of generation of electrical energy usually involves combustion or processing of fossil fuel and carbon materials which have severe adverse effects on the environment. The amount of dangerous carbon by-products produced depends on the amount of energy generated which in turn depends on the maximum demand by the consumers.

The increased tariff plan coupled with the increasing environmental concern on energy consumption gives rise to the need for the monitoring and optimization of energy by the consumer. Existing smart energy meters monitor the energy consumed but this is not very effective as it measures net energy consumed and does not take into consideration the energy consumed by individual appliances.

A more effective approach would be to measure and monitor energy usage on each electrical appliance (load) so as to determine which appliance consumes the most energy and what measures can be taken to optimize the consumption. An energy management system using this approach is discussed below.

The purpose of the smart home energy management system (SHEMS) is to achieve real time, in depth monitoring and direct control of all the electrical appliances in the household wirelessly by using a mobile device owned by the consumer. This is in order to enable proper understanding of the energy consumption in the home.

The smart energy management system will accomplish the following key objectives.

- The design and development of a comparatively low cost energy management system.
- The monitoring of energy consumption by individual electric appliances over different time periods.
- Creation of a simple and centralized interface between the consumer and the connected electrical devices.

2 Literature Review

2.1 Energy Measurement

Power (P) can be defined as the work done per unit time and is measured in Watts (W). It is obtained directly from multiplying current (i) and voltage (v) at any time t. This is given as:

$$P = i(t) \times v(t) \quad (1)$$

Energy (E) can then be defined as the total power expended over time. The energy delivered by a power source into a load can be expressed as:

$$E = \int i(t) \times v(t)\, dt \quad (2)$$

In integrated circuits, the analog voltage and current signals are converted to discrete samples using an analog to digital converter and the required energy data is obtained. The analog

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voltage signal is measured by connecting a series of voltage divider circuits and a transformer directly to the alternating current line, while the current signal is measured using a current transformer connected to a shunt resistor or a current sensor.

A Hall Effect sensor is a transducer that varies its output voltage in response to a magnetic field. When a beam of charged particles passes through a magnetic field, forces act on the particles and the beam is deflected from a straight path. The flow of electrons through a conductor is known as a beam of charged carriers. When a conductor is placed in a magnetic field perpendicular to the direction of the electrons, they will be deflected from a straight path. As a consequence, one plane of the conductor will become negatively charged and the opposite side will become positively charged. The voltage between these planes is called Hall voltage. The voltage is a linear representation of the current flowing through the conductor and can be measured by a connected microcontroller. For the ACS712 sensor, the calibration is set at 66 millivolt per amp (mV/Amp).
The microcontroller obtains the voltage signals representing the supply voltage and current across the device and using certain processes produces the required energy and power readings. The analog input structure greatly simplifies sensor interfacing by providing a wide dynamic range for direct connection to the sensor and also simplifies the antialiasing filter design. A high-pass filter in the channel removes any dc component from the signal, eliminating inaccuracies in the real power calculation which may appear due to offsets in the voltage or current signals. The real power can be calculated by the multiplication of the voltage and the current. The energy is obtained by passing the power signal through a low pass filter and the summation of the filtered signal gives the required energy data.

The objective of the energy measuring system is to use certain devices to measure voltage, current and power in real time. There are two major categories of energy reading devices: electromechanical and electronic (digital).

Several methods have been employed which include the Supervisory Control and Data Acquisition (SCADA) for measurement of energy data. SCADA was used as a standard for obtaining different information about a home (temperature, lightning, heating etc.) for energy conservation [3].

Supervisory Control and Data Acquisition (SCADA) is a control system architecture that uses computers, networked data communications and graphical user interfaces for high-level process supervisory management, but uses other peripheral devices such as programmable logic controllers and discrete PID controllers to interface to the system. The operator interfaces which enable monitoring and the issuing of process commands, such as controller set point changes, are handled through the SCADA supervisory computer system. However, the real-time control logic or controller calculations are performed by networked modules which connect to the energy sensors.

The SCADA concept was developed as a universal means of remote access to a variety of local control modules. In practice, large SCADA systems have grown to become very similar to distributed control systems in function but using multiple means of interfacing with several systems at once. Despite their numerous capabilities, there are however concerns about SCADA systems being vulnerable to cyber terrorism attacks [4].

Another method of energy measurement was done by measuring the voltage and current signals separately then multiplying the result to get the power. The instruments required for the measurement included dynamometer and thermistors which were electromechanical in nature [3], [4].

O.Homa Kesav and B. Abdul Rahim made use of an ADE7757 energy metering IC for energy measurement but also used a GSM module for wireless communication. The ADE7757 is a low cost, single-chip solution for electrical energy measurement. The ADE7757 is a highly integrated system comprised of two ADCs, a reference circuit, and a fixed DSP function for the calculation of real power. A highly stable oscillator is integrated into the design to provide the necessary clock for the IC. The ADE7757 includes direct drive capability for electromechanical counters and a high frequency pulse output for both calibration and system communication [5].

Existing commercial energy meters such as AlertMe and EnviR have been used for energy measurement. Both meters use the electromechanical effect for measurement. They have the advantage of being easy to install because of their non-invasive nature but are relatively expensive and not very accurate. [8] The electromechanical devices in general have the limitations of producing large offsets in measurement and have very limited interface capability.

Due to inaccuracy and the difficulty encountered in interfacing with external devices by the electromechanical devices, The PIC16F887 or the 78M6613 can be used for energy measurement. Here, two basic sensors are employed; voltage and current sensors. The voltage sensor built around a step down element and potential divider network senses both the phase voltage and load voltage. The second sensor is a current sensor which senses the current drawn by the load at any point in time. It is built around a current transformer and other active devices (such as voltage comparator) which convert the sensed current to voltage for processing. The output from the sensors is passed through a signal (or voltage) conditioner which ensures matched voltage or signal level to the control circuit, it also contains a signal multiplexer which enables sequential switching of both signal to the analogue input of the peripheral interface controller (PIC).

In a typical application, the 32-bit computer engine (CE) of the 78M6613 sequentially processes the samples from the voltage inputs and calculates the active and reactive power. These measurements are then accessed by the MPU, processed further and output using the peripheral interfaces available to the MPU [6].

2.2 Data Transmission

This involves the collation and transmission of energy data obtained from the energy measuring device wirelessly to a point where the data can be accessed and analyzed. Most existing energy management systems use either a GSM module or a Zigbee device. A GSM module is a Quad-band device used for receiving and sending data wirelessly. It is very compact in size and easy to use as plug in GSM modem. The module is designed using a 5-volt DC Transistor-Transistor Logic (TTL) interfacing circuitry, which allows the user to directly interact with 5V Microcontrollers (PIC, Arduino, 8051, etc.). The GSM modem uses a Transmission Control Protocol/Internet Protocol (TCP/IP) stack to enable internet connection using general packet radio service (GPRS). The module can be interfaced with an Arduino controller using USART (Universal Synchronous Asynchronous Receiver and Transmitter) which features serial communication [7].

The GSM module can also be used with an Arduino microcontroller in which PIR sensors and current/voltage sensing circuits send data over the internet to a wiki page [8].

Zigbee modules are intended to be simpler and less expensive than other wireless personal area networks (WPANs), such as Bluetooth or Wi-Fi. Applications include wireless light switches, electrical meters with in-home-displays, traffic management systems, and other consumer and industrial equipment that require short-range low-rate wireless data transfer [9].

Its low power consumption limits transmission distances to 10–100 meters line-of-sight, depending on power output and environmental characteristics. Zigbee devices was observed to be able to transmit data over long distances by passing data through a mesh network of intermediate devices to reach more distant ones [10].

2.3 Energy Monitoring and Consumption Analysis

This is the major part of the project because it is where the actual energy management processes take place. These processes include: a real time billing based on the dynamic energy pricing; visualization of the energy profile and history of all home appliances; load forecasting and scheduling based on previously consumed energy; and interaction with relevant third parties (utility companies).

Amir-Hamed Mohsenian-Rad et al. proposed the scheduling of the consumption of energy at times that are optimal for the consumer using mathematical methods such as game theory and distributed algorithms for the load scheduling. Integration with the Distribution Company and smart meters was also suggested to know peak demand times for a range of users within a grid [11]. A. Saha et al. also proposed the use of a smart home energy management algorithm but with emphasis on renewable energy [12].

Another brilliant method suggested was the use of learning algorithms to identify different appliances using whole household readings. This method is based on the theory which states that different appliances have different "digital signatures" when consuming energy and algorithms can be made to identify appliances based on these signatures. These digital signatures are raw recordings of single-device power consumption [13].

Daniel Schweizer et al. also proposed the use of machine learning to implement energy saving based on consumer data but instead of working with just the load, this also involved finding patterns in consumer behavior and also implementing a recommender system that suggests the inferences obtained from the machine learning algorithm [14].

Quiran Hu and Fanyang Li also discuss the use of machine learning for the purpose of energy management based on real time pricing. This paper also proposes the use of a Naïve-Bayes classifier or a hidden Markov model as suitable machine learning algorithms. He also suggests the use of other non-energy sensors like PIR sensors for analysis of human activity with respect to energy usage [9].

For the control of the devices, K.N Ramli and A. Joret used an Arduino microcontroller and integrated it with the switches and relays which were connected to different appliances. PIR sensors were used for control of lighting and air conditioning [8].

3 System Design

The SHEMS was designed to utilize low cost components that ensured the desired functions of measuring, processing, transmitting and analyzing home appliances. The system architecture can be seen in figure 1.

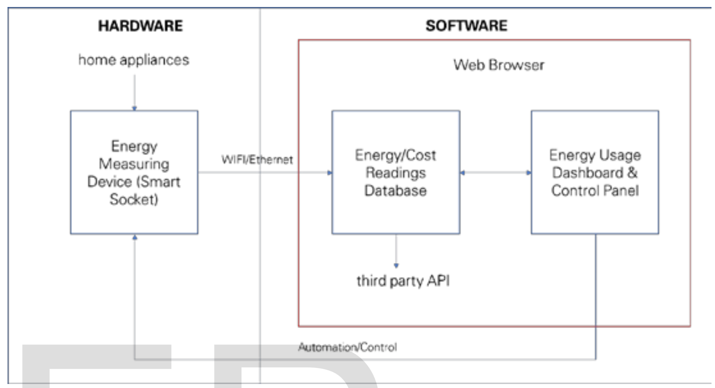

Figure 1: System Architecture for Home Energy Management System

3.1 Hardware Design

The arrangement and connection of all hardware components and tools used to design the energy management system could be grouped under 2 major units: Energy Measuring Unit and the Data Transmission Unit.

The Energy measuring unit is the part of the system that measures the required electrical quantities i.e. voltage, current, power and energy. The current measurement was done using an ACS712 Hall Effect sensor while the voltage measurement was done using a series of voltage divider circuits. For a practical measurement, not only voltage and current amplitudes, but also phase angles and harmonic content changed constantly. As long as the ADC resolution was high enough and the sample frequency was beyond the harmonic range of interest, the current and voltage samples, multiplied with the time period of sampling yielded an accurate quantity for the momentary energy. Summing up the momentary energy quantities over time resulted in accumulated energy. The ADC converted the analogue signals to its digital equivalent; both signals from the voltage and current sensors were multiplied by the means of embedded software in the Arduino microcontroller.

The voltage was measured using a voltage divider circuit. The reason for this is because the Arduino input pin voltage must not exceed 5V and the mains voltage to be measured is in the region of 220V – 240V. To achieve this, the power supply unit is integrated with the voltage divider such that the 12V is stepped down to a voltage lower than 5V and then rectified to get a DC value. The values of resistors picked for the voltage resistor circuit are 10ohms and 20ohms. The desired output ac voltage is obtained across the 10ohms resistor and sent into the rectifier input.

The Data Processing and Transmission system is responsible for the processing of the readings measured by the energy measuring system and transmitting the data to the online database. For the processing of electrical readings, the Arduino Uno was selected. This was due to the relatively cheap price and ease of installation and simple microprocessor that did not require a complicated circuit. The Arduino UNO is a microcontroller board based on the ATmega328 microcontroller and 16U2 USB-to-serial converter chip. It consists of 6 analogue ports, 14 digital ports, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, voltage regulator and reset button. The Arduino Uno can be programmed by the Arduino IDE, an integrated development environment and the Arduino language.

The Arduino Ethernet Shield allows an Arduino board to connect to the internet. It is based on the W5100 Ethernet chip. The W5100 provides a network (IP) stack capable of both TCP and UDP. It supports up to four simultaneous socket connections. The Ethernet library is used to write sketches that connect the Arduino to the internet. The Ethernet shield connects to an Arduino board using long wire-wrap headers which extend through the shield. This keeps the pin layout intact and allows another shield to be stacked on top.

3.2 Energy Software Design

This is the part of the system that is accessible to the consumer and which is involved with the monitoring, analysis, processing, optimization and control of the connected appliances. The application is built using web technologies such as HTML, CSS, JavaScript and PHP).

1) Energy & Appliance Database: The energy data and profile of the home appliances are sent through the Ethernet shield to the Energy & Appliance Database. For this project, this database is hosted on a local server and is managed by a database management system, a software application that creates and manages databases. The key components include:
    - Energy Consumption History: This feature will show historical data of the total units consumed and will contain a graphical representation of this data over a period of time.
    - Device History: This feature will specialize in the energy consumption history for a particular connected electrical device. This will also give in depth analysis of a device including frequency of usage and how it affects the bill.
    - Electricity Bill History: This feature will provide the consumer with the data of the electrical bill over a set period of time.

2) Energy Usage Dashboard: This is the presentation layer of the energy management system that is accessible to the consumer. The dashboard was built using HTML, CSS and JavaScript and displays the readings stored in the database through graphs and figures as shown in figure 2.

Figure 2: Energy Usage Dashboard

The key features include:

- Real time Energy: this displays the real time energy usage of each device and the overall real time energy consumption.
- Periodic load curve: this allows the user to see a graphical representation of the energy consumed in a set period of time i.e. days, hours, months, years.
- Real time cost bill: This feature lets the consumer know how much the consumer is spending on electricity consumption per device and on an overall basis. This multiplies the tariff with the energy consumption.
- Usage limit: This feature allows a user to set a limit to which the consumer wants to pay as an electricity bill for the incoming month. This will aid the user in cost saving.

4 Testing and Results

In this chapter, the discussion and results obtained were based on the hardware design and software development. It involved the implementation, fabrication, testing and modification of the prototype. Experiment based on the full system is included with corresponding analysis. Calculations were done to compare the theoretical values and the experimental values.

4.1 Simulation

The circuit diagram for the energy measuring circuit was first designed and simulated using the Proteus 8 professional application as shown in figure 3.

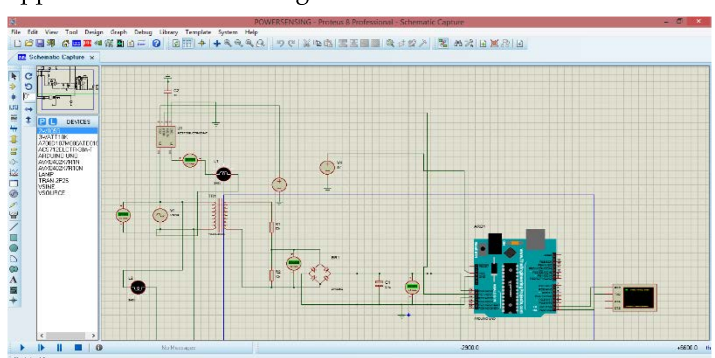

Figure 3: Simulation of the SHEMS on Proteus 8

Two 60W and 100W bulbs were used as tests loads for the simulation. An extract of the output obtained from the Proteus virtual terminal is shown in Table 1. From the readings obtained, it can be seen that the results obtained are seen to be typical with the expected ratings of 60W and 100W rated bulbs.

TABLE 1
PROTEUS 8 SIMULATION RESULTS

Device	Voltage	Current	Power	Energy (t = 2s)
60W rated bulb	239V	0.26A	62.57W	0.000035kWh
100W rated bulb	239V	0.41A	100.1W	0.000097kWh

4.2 Testing and Results

After simulation, the project was tested on a breadboard using the procurred hardware components before being soldered and screwed firmly to the board as shown in figure 4.

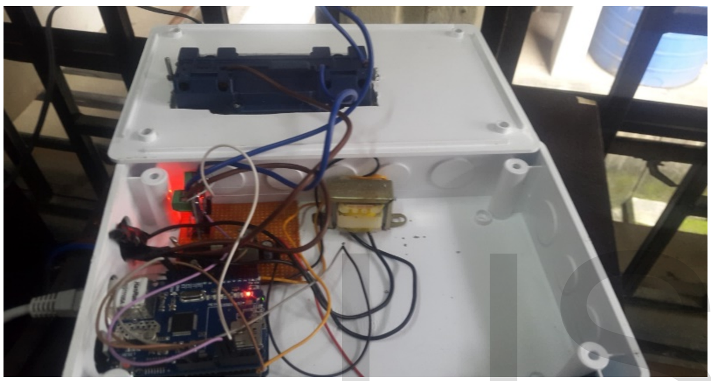

Figure 4: Snapshot of the coupled components

The finished project was able to measure and manage two devices with ratings up to 7.2kW. The results for two devices, a 90W rated laptop and a 16W rated router, connected to the system are shown in figure 5.

Figure 5: Energy Monitor displaying the readings for the connected appliances

As a means of supply side management, when the loads were switched OFF for longer than a preset operating time, a notification was sent to the energy utility company to stop supply of power to the home.

5 CONCLUSION

The energy management system developed is able to adequate measure, monitor, analyze and present the consumer with information on the electricity consumption in the home using low-cost electrical components and a web application. This enables the consumer to modify usage habits and implement energy efficient strategies for consumption. Also, in-built features such as setting usage limits and interacting with the utility company for load scheduling can lead to further energy savings and significant reduction in electricity bill paid.
Despite the adequacy of the system, further features and functionality that could further enhance the efficacy of the system are recommended below:

1) Appliance automation and use of machine learning algorithms to predict consumer behavior and identify patterns for load scheduling and energy consumption
2) Creation of mobile applications and even a standalone unit for ease of use and diversity of operation.
3) Complete integration into the operation of the energy utility companies to create smarter grids for the entire country.

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