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Original Article

Design and Development of an Energy Management System for Residential Consumers

Miriam S. Galvez

Electrical and Electronics Engineering Department, College of Engineering, Tarlac State University Tarlac, Philippines.

Corresponding Author : msgalvez@tsu.edu.ph

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Abstract - *Proper management of the electrical system at the residential level and awareness of the homeowners' energy usage contribute to the efficient use of electrical energy. Through the development of a mobile application, homeowners can turn on and off devices when not in use and monitor their energy usage using their phones. The study focused on designing and developing such applications that provide remote access for users. The circuit comprises a microcontroller, voltage and current sensors, relays, and circuit breakers. Meanwhile, convenience outlets are connected to the electrical branches. During testing, all buttons displayed what they were supposed to show or do; however, there was a mishap due to an unstable Wi-Fi connection and some faulty electrical connections. Hence, the researchers recommend utilizing the system in a 2.4 GHz network.*

Keywords *- Internet of Things, Controlling electrical systems, Energy consumption, Energy awareness, Energy Blynk application.*

1. Introduction

The world's energy demand is continuously growing. The Department of Energy (DOE) reports that the total final energy (TFE) in 2020 was 32.4 million tons of oil equivalent (MTOE). [1] At the core of this demand is the issue of global warming since a substantial chunk of CO2 emissions comes from burning fossil fuels to generate electricity. [2] Studies on energy demand in households have assumed higher importance [3], and this endeavor leads to a need for action [4] contributing to energy-saving measures. [5, 6] In general, the energy demand is associated with population and socio-economic status. [7-9] The increase in demand from households may be partially attributed to new end-users, comfort and amenities, and new types of equipment. [10] Aside from these factors, residential energy consumption is also associated with behavioral, technological, climate, and some other factors relating to the materials used in the building, technical characteristics, and architectural traditions. [11] In terms of behavioral aspects, the influence on choices and decisions is apparent, especially on the physical characteristics of buildings and systems. [12] Today, many appliances are equipped with remotes, which allows them to be on standby mode. Moreover, these devices translate to $19 billion a year – about $165 per U.S. household on average. [13] Appliances may consume from 0.1 to 3 Watts during standby, translating to up to 3.34% energy savings. [14] At this rate, power losses may seem insignificant, but as the trend of purchased household appliances increases, losses will also increase to this effect. [15] Understanding the behavior of occupants is necessary to provide an intervention. [16] There is often a significant discrepancy between consumers' knowledge, values, and intentions and their observable energy behavior. [17] A study on energy efficiency in household energy consumption asserts that raising individual consciousness, having control over power consumption, and receiving correct feedback on power usage will all significantly enhance electricity use.[18] Studies show that when provided information, people will become more conscious of the amount of energy they use, leading them to choose alternate energy-use strategies, supporting the idea that we can use less energy. [19-20] Hence, giving real-time data is essential for modifying how we utilize electricity. [21] This can be done by interconnecting appliances via the internet to control and monitor energy usage by integrating sensors, apparatus, and technology that can communicate with people through embedded systems. [22] The features of such technology can mimic the operations of an energy management system for small-scale applications.[23] Similar studies used the Global System for Mobile Communication (GSM) in their design of Energy Management Systems [24, 25] due to its ease of use and adaptability. [26] However, it has a lot of connectivity and coverage issues. [27] Aside from this, other researchers used current sensors only. [28, 29] In this study, the researchers used Wi-Fi, which typically offers faster data transfers than GSM. Aside from being low-cost, the Wi-Fi microchip can be especially integrated with any Arduino platform. [30] Also, instead of using an LCD to display current and voltage parameters, the researchers focused on using the Blynk app in building the IoT systems based on open-source platforms so that they can be used on Android and iOS devices. To control essential parameters, the researchers opted to use Arduino Mega due to its versatility and low-cost features. It can also be integrated into IoT, enabling the user to control the switches and electrical appliances with a smartphone. [31] The circuit design was also added with current and voltage sensors for more accurate reading, real-time monitoring, easier data perception [32], and accurate energy usage reading, leading to a quick energy management technique. [33]The goal of the study is to provide a means for household owners to contribute to the reduction of energy usage by designing and developing an IoT-based energy management system. Homeowners can remotely monitor and control their devices and equipment. This way, they will be able to keep track of their household's energy usage, which in turn could help them become more responsible in using energy.

Specifically, the researchers aim to achieve the following objectives: a) to design an IoT-based energy management system that will monitor and control electrical branch circuits integrating a microcontroller, b) to develop a mobile application that will enable the user to control the branch circuits and monitor real-time energy consumption, and c) to evaluate the functionality of the app to monitor and control the electrical system.

2. Materials and Methods

The main goal of the study is to produce an energy management system for more efficient monitoring and control of energy usage by a residential owner by providing them with a mobile application that is simple enough for them to use. This can be done by integrating a microcontroller-based circuit to control and monitor an electrical system. The integration process can be facilitated using a mobile application for remote access.

The process of development of the application is illustrated in Figure 1. It begins with the design of the graphical user interface, where buttons and labels are placed in the main window of the app. Buttons are then given their respective program codes. In the testing phase, buttons are checked whether they are doing what they are supposed to do. When problems are encountered during the testing phase, editing the program codes or troubleshooting the physical circuit is done. The circuit comprises a microcontroller, voltage and current sensors, relay modules, and a Wi-Fi module. Sensors read current and voltage in the branches while relay modules control power in the branches. The system's output data goes to a dedicated server and then to the mobile application to display the voltage, current and power consumption. The electrical load consists of convenience outlets. The user can turn on/off branch circuits from the mobile app. Meanwhile, the electrical loads used during testing were household appliances like electric kettles, electric pots, coffee makers, electric fans, ice makers, and mobile devices like phones and tablets. The researchers used a combination of these appliances to create a total of 300 watts for Branch 1, 400 Watts for Branch 2, and 350 Watts for Branch 3. A matrix of expected functions was used for the functionality test of the mobile application to determine its ability to control the electrical branches and display the user's energy consumption, including the cost and the trend of usage.

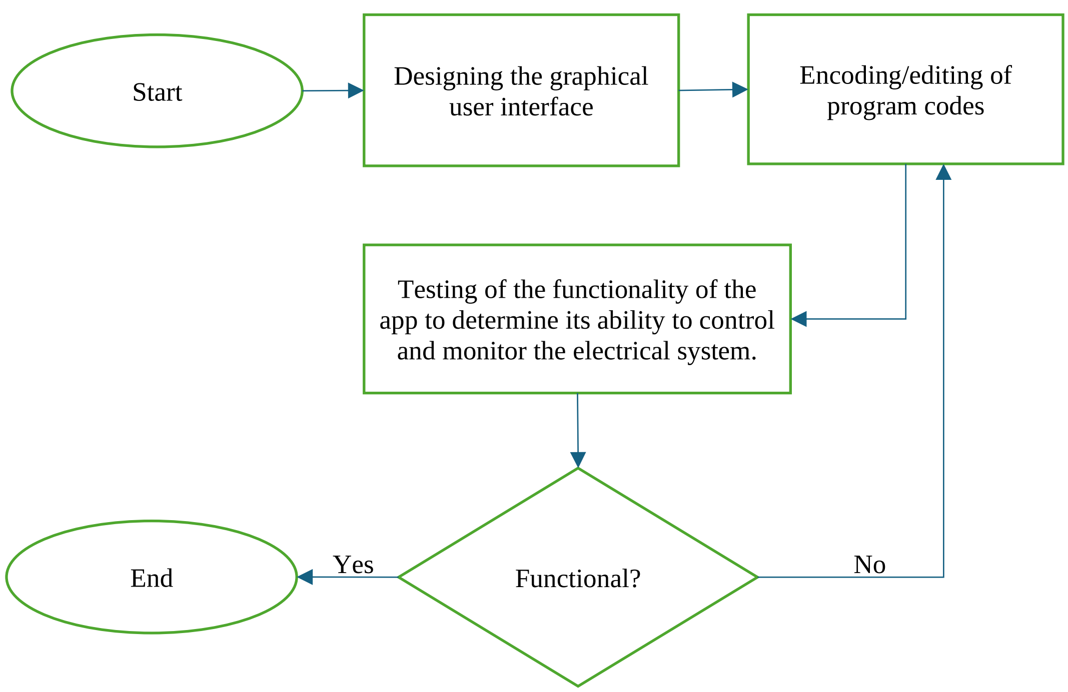

Fig. 1 Development process of the mobile application

As part of the development of the application, five participants were asked to try the application to evaluate the system. They used the app from the point of connecting the system to Wi-Fi to testing each button in the user interface. Their insights were noted as to what problems they have encountered and what they think are the best features of the application. The comments of the participants were made as the basis for developing further the programming codes and user interface.

3. Results and Discussion

3.1. Design of the Energy Management System

The schematic diagram of the system is shown in Figure 2. The circuit has a submain overcurrent protection device and three branch circuit breakers.

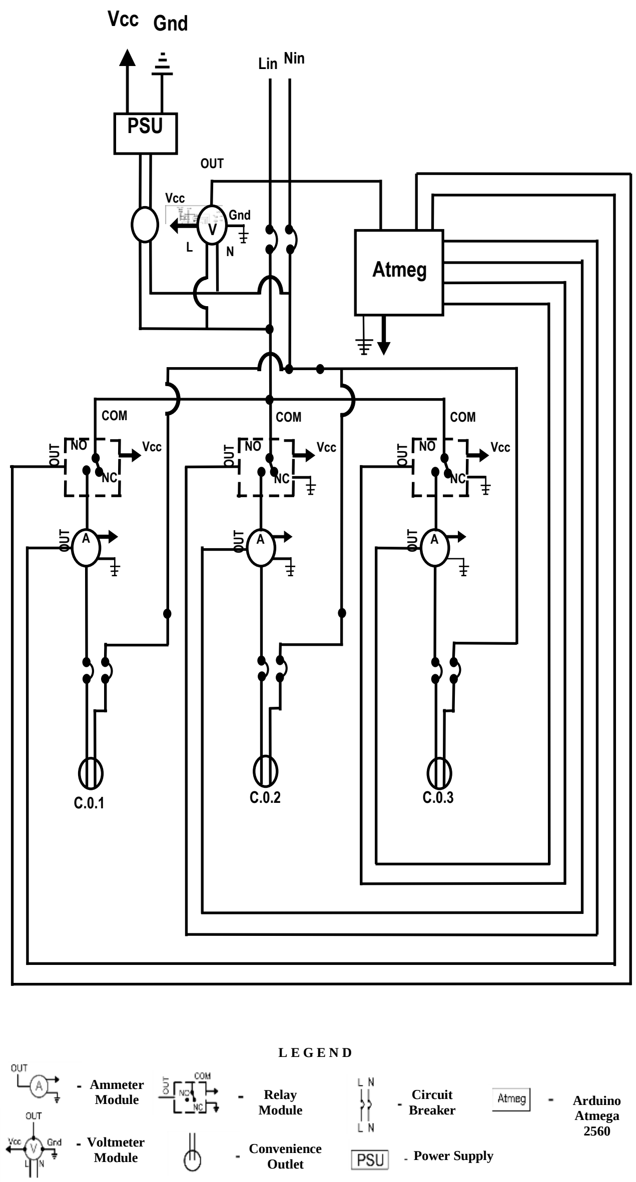

Fig. 2 Schematic diagram of the energy management system

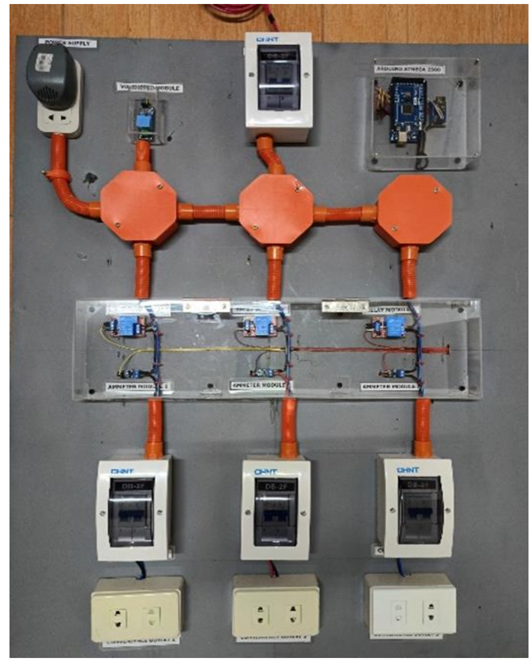

Fig. 3 Actual circuit of the energy management system

It has three current and voltage sensors that will read the current and voltage in the lines. The readings are inputs for the computation of energy used depending on the connected loads for a particular time. The Wi-Fi module is connected to the Arduino microcontroller, which will enable the user to control and monitor the circuit through a mobile phone. The user can either turn on/off the supply of electricity in each branch and will also see the energy consumption, corresponding cost of energy and the trend of energy usage of the homeowner. The electrical system of the residential model used for the energy management system is a 230V, single-phase, two-wire, grounded 60Hz. Figure 3 shows the photo of the actual circuit.

3.2. Development of the Mobile Application

The researchers encoded the program using Blynk version 1.43. The mobile application's user interface, seen in Figure 4, has a main window showing buttons for every room in the house. The said rooms correspond to the electrical branches in the physical circuit, that is – Branch 1 for the Bedroom, Branch 2 for the Kitchen, and Branch 3 for the Living Room. For the processing of voltage and current readings, the researchers used a particular Arduino library called "EmonLib.h", which can be downloaded for free from the databases of the Arduino website. Additionally, the set of codes used to read the voltage and current from the 3 pairs of sensors are shown below.

```
float Voltage1 = emon1.Vrms;
float Current1 = emon1.Vrms;
float Voltage2 = emon1.Vrms;
float Current2 = emon1.Vrms;
float Voltage3 = emon1.Vrms;
float Current3 = emon1.Vrms;
```

3.3. Functionality of the Mobile Application

Figure 4 also shows two scenarios, the left one has all buttons set to ON, indicated by the green circles. Meanwhile, the scenario on the right has buttons set to OFF. In this case, the circles have no color, meaning that all electrical loads do not function in all rooms. The mobile app provides real-time estimates of the total energy consumption in kilowatt-hour and the energy cost in Philippine peso. The energy cost is assumed to be 11 Philippine peso per kWh.

Additionally, the mobile app displays graphs of the energy usage of a residential consumer, allowing visuals for energy monitoring. Different load scenarios were done to evaluate the app's ability to correctly display the energy consumption in kWh, the cost of energy, and the graph of energy consumption.

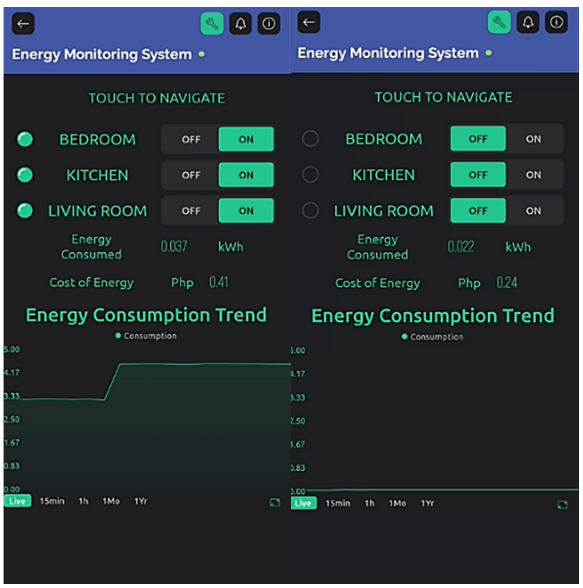

Fig. 4 Graphical user interface of the application

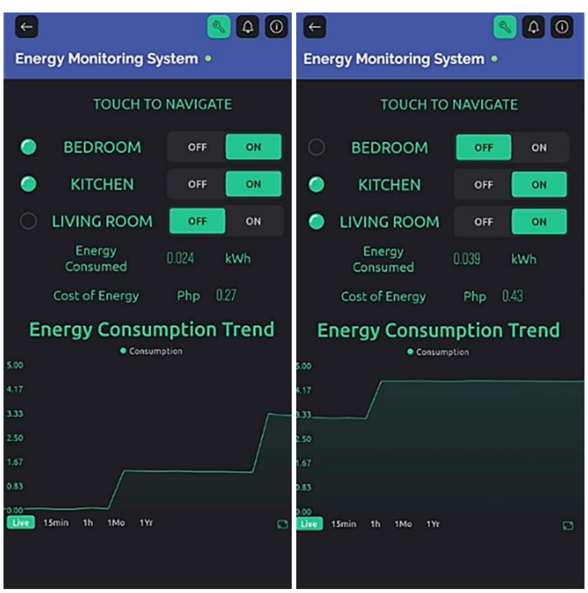

Fig. 5 Two rooms turned on at a time

Figure 5 shows scenarios where rooms are turned ON two at a time, while Figure 6 shows rooms are turned ON one at a time. When loads are turned on or off, the graph, energy cost and consumption change accordingly. Meanwhile, the readings of energy consumed and the cost of energy in the app are depicted in Figure 7. The photo displays the readings during no load. Interestingly, the mobile app displays a reading of 0.022 kWh, which is translated to 0.24 Philippine pesos of energy cost. Upon investigation, it was concluded that the reading comes from the energy consumed by the circuit's microcontroller, relays, and wires. To illustrate the impact of the developed system on energy efficiency, the researchers estimated the computed energy consumption. If all 7 appliances were plugged into the convenience outlets and each appliance consumed at least 1 Watt on standby mode, the estimated energy consumption for 24 hours would be Php 1.85, translating to Php 675.25/year. Meanwhile, the United States Environmental Protection Agency estimates that 0.024 Metric tons of CO_2 emission for a year will result from these appliances being on standby mode. [34] Tests were conducted to determine whether the buttons can control and monitor the electrical system.

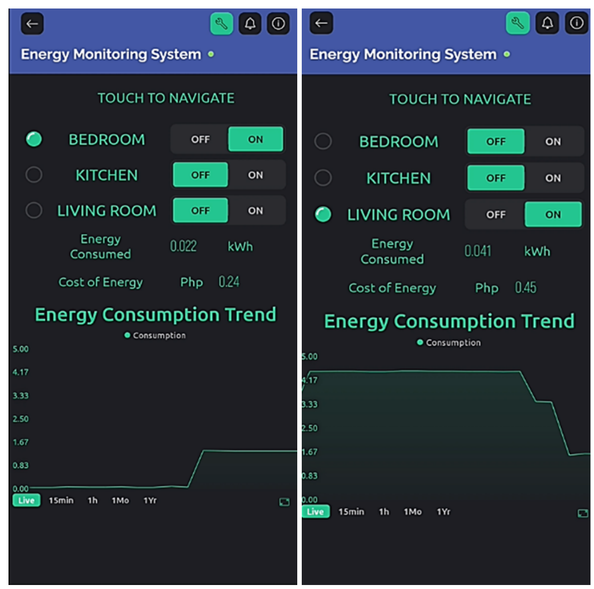

Fig. 6 One room turned on at a time

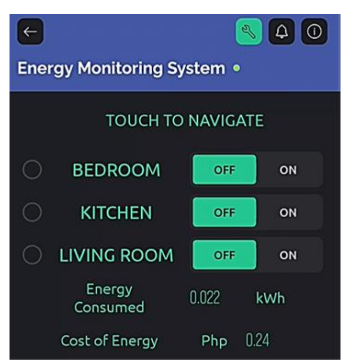

Fig. 7 Displayed values of energy consumption and cost in the mobile application

Table 1. Functionality test results of the mobile application

No.	Action	Expected Results	Test 1	Test 2	Test 3	Comments/ Problems Encountered During Failed Attempts	Corrective Action Taken
1	System Start Up	Synchronized turning on of modules and mobile app	Failed	Failed	Passed	The Wi-Fi module does not connect with the link server due to poor connectivity or the area of coverage is limited.	The Wi-Fi module should be linked to the router.
2	Clicking on the on/off toggle switch for Branch 1	The loads connected to Branch 1 will turn on/off.	Passed	Failed	Passed	Delayed response of relays due to poor connectivity Loose connections of modules	Use of a stable internet connection Fixed/soldered connections
3	Clicking on the on/off toggle switch for Branch 2	The loads connected to Branch 2 will turn on/off.	Failed	Failed	Passed	Poor connectivity Loose connections of modules	Use of a stable internet connection Fixed/soldered connections
4	Clicking on the on/off toggle switch for Branch 3	The loads connected to Branch 3 will turn on/off.	Passed	Failed	Passed	Poor connectivity	Use of a stable internet connection
5	Display of Energy Consumption in kWh	The app displays in real-time the energy consumption	Passed	Passed	Passed	None	N/A
6	Display of Cost of Energy in Php	The app displays the monthly estimate of the cost of energy in Php	Passed	Passed	Passed	None	N/A
7	Display of Energy Consumption Trend	The app displays the trend in energy usage	Failed	Failed	Passed	The scale of the graph is too big for the rating of the loads. Wrong settings in Blynk app	Adjusted the scale of the graph. Adjusted settings in the Blynk app

Table 1 shows the matrix of the result of evaluating the button functions. The major drawback encountered by the researchers was poor Wi-Fi connectivity. The Wi-Fi module (ESP8266) utilized by the researchers is limited to a frequency of 2.4 GHz. The problems encountered during the system testing may be due to this fact. There may be fluctuations in the signal, from lower to higher frequency or vice versa, which may result in errors in the system's response. A possible solution could be to ensure that the mobile device and the Wi-Fi settings are set to a 2.4 GHz network.

3.4. User Experience (UX) and Engagement

The participants who evaluated the system noted that the user interface is exactly what they need in an energy management system designed for a residential home. According to them, it has a simple design and does not overwhelm the users with complicated features.

One of the evaluators pointed out that a similar application he had tried before had too much information on the display, which is not useful for average homeowners. They want a straightforward solution to control their devices and monitor their energy usage. The only problem they encountered during testing was the intermittent Wi-Fi connection. They suggested setting the Wi-Fi settings to a fixed frequency.

3.5. Sustainability and Future Research Directions

The developed system may be integrated into the electrical system of households as part of their safety and energy-efficiency improvements. The system may be included during the planning stage of new houses, while for existing ones, the system may be externally added to the electrical system. Additionally, the system has the potential for multi-dwelling facilities like apartments and malls.

4. Conclusion

The relays are actuated when the ON/OFF buttons in the app are tapped, facilitating the turning on/off of the load branches. Energy consumption and cost are displayed in the mobile application as expected. The buttons of the application are functional except when there is an unstable Wi-Fi connection, noting an average of 5-second delay; hence, it should be ensured that the Wi-Fi settings are fixed to 2.4 GHz frequency. There is also minimal energy cost to operate the system.

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