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Digital Energy Monitor: Design, Simulations and Prototype

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Abstract

This paper demonstrates the design and implementation of a GSM based digital energy monitoring device. Firstly fuzzy based model is developed to replicate the characteristic of current and voltage sensors. The entire system is also studied and simulated in terms of utility side supply, load, microcontroller digitization and GSM communication. A virtual data sharing technic is also studied for the proposed system using state flow logic. A prototype system is verified real-time with its test and verification phase results. In this work, remote monitoring of electricity has been made easier for the utility. Demand side management is also presented as customers can instantly get their electricity consumptions when requested. Further, an effective overcurrent monitoring system has been embedded along with a backup battery source. Results obtained from the experiments prove that with this emerging technology it is possible to move towards a smarter grid at a rapid and cost effective way.

Keywords: *Remote energy monitor, Smart metering, Protection, Embedded system.*

1. Introduction

Energy is an essential input to all aspects of human life. All levels of human activities depend on it. However, an increase in the energy consumption and its rising cost per unit has informed the consumers of the need to effectively utilize and monitor their energy consumptions. It is obvious that low energy consumption would be highly recommended whether for domestic or industrial illumination. However, whether these appliances have high or low consumption capacity, it becomes necessary to have an effective energy metering system that is capable of keeping the consumers well informed and updated. Some new technological advanced energy metering systems were discussed as effective means of monitoring and displaying power consumptions (Ashna *and* George, 2013; Palaniappan *et al*., 2005; Sivaram, 2015). It has been recorded that widely used conventional energy monitoring devices have lack of configurability and poor accuracy. In addition to that, detection of tampering is near impossible. Through technological innovations, it is now possible to implement an energy efficient metering system that takes into consideration the factors of precision, accuracy and error limitations. Prepaid metering requires advance payment for energy consumption whereas postpaid involves payment after usage. Energy meters have also been designed recently that are now capable for operating in high ambient temperatures and adverse conditions with high accuracy and precision (Abbas *et al*., 2016). A recent study has shown the use of Monte Carlo method to reduce the error in readings from ADC which adds to better precision and accuracy of digital meters (Xiaojuan *et al*., 2016).

Pacific Island Countries (PIC) has yet to emerge in the implementation of prepaid metering technology. There has been some developments and research on the implementation of smart energy monitoring devices using different means of communications as reported in the literature (Okafor *et al*., 2017). Most commonly, GSM technology has been used for implementation of a smart energy monitoring device by a group of researchers. Islam *et al.* (2012) also used the GSM technology was also used to design a similar concept. In the design, the voltage and current sensors are connected to the ADC filter for achieving a converted unit that could be read by the microcontroller. A real time clock, memory (internal cache) and a LCD were also embedded to the system. After logging of the data, the bill is calculated and sent to the customer and utility through SMS. The recorded long time data is also saved to the external servers. Okafor *et al*. (2017) developed an IoT based smart metering system while analyzing its integration procedure with extending wireless GSM and WiMax technology.

Radiofrequency has also been used to establish communication for metering devices. Rodney *et al*. (2007), has also focused on radiofrequency communications as a link between the grid and the consumer. The design consists of a microprocessor (ATmega 8) and IC (AT7751) for data processing and current measurement. After the total consumption is calculated, it is sent via RF module. Ethernet module is also connected through a web link to allow data to be tracked. Another work by Primicanta *et al.* (2009) also consisted of Atmega 8 microprocessor and AT7751. A relay and IR receiver are also used in the design. Measurement is done through sensors and the consumption is transmitted to the customer and service provider through GSM. The load can also be disconnected/ connected through GSM commands.

Smart meters are regarded as game changers as it can be shown to be successful in measuring current, power consumption and also processing the cost incurred by a customer (Okafor *et al*., 2017; Ahmed *et al*., 2011; Jain *et al*., 2012; Thanth and Borole, 2013). They depicted the concept firstly for home automation and offers an alternative way for customers, including utility companies to keep track of energy consumption rate and billing anyhow and anywhere. Energy consumption data is collected and visualized. Recently reconfigurable devices are recommended for such system. The collected data can be sent through Wi-Fi to the home's wireless router and to the base station. LCD is also recommended for display of the data along with design of GUI embedded system for calculation and analysis.

This paper suggests most viable solution on digital energy monitoring system using GSM mobile networks for energy management strategy. All experiments are performed in Matlab/Simulink programming environment to validate the prototype. This proposed device is capable of measuring the power accumulated along with the amount in dollars of electricity consumed. The customers would be able to attain their energy consumption through calling the device and getting the usage through SMS by automatic call diverting by the device. Also, every 30 days the total consumption would be sent to the utility and the meter will be reset. The basic display of power consumption as well as overcurrent warning is displayed on LCD as a part of embedded features of the system.

2. System Overview and Operation

Overall system block diagram of the proposed digital energy monitor is shown in Figure 1. The current sensor is connected in series to the load. It serves as a means of current measurement which is translated to voltage readings as input to the microcontroller. GSM shield is considered to be bidirectional in data flow. Incoming data is acquired through GSM shield and processed through microcontroller. Outgoing data is processed by microcontroller and sent through the GSM shield. LCD is used to display the ongoing readings of kWh and dollars (FJ$) consumed. Buzzer is incorporated in the warning system. The warning state is activated when the current (I_{rms}) value increases above 16A. Microcontroller is responsible for processing data by doing conversions into kWh and dollars. It also oversees requests from the GSM shield and sends the required data through GSM. Automatic reset at every 30 days is also done by the microcontroller.

The microcontroller and the components are powered up though a charger circuit employing two sources of supply. The sources are toggled as per their availability. The mains supply is given the first priority. If the mains supply goes out, the backup 9V rechargeable battery is switched on. The battery goes into recharge mode when the mains supply is active and upon 100% state of charge, the charger circuit cuts of the supply to battery.

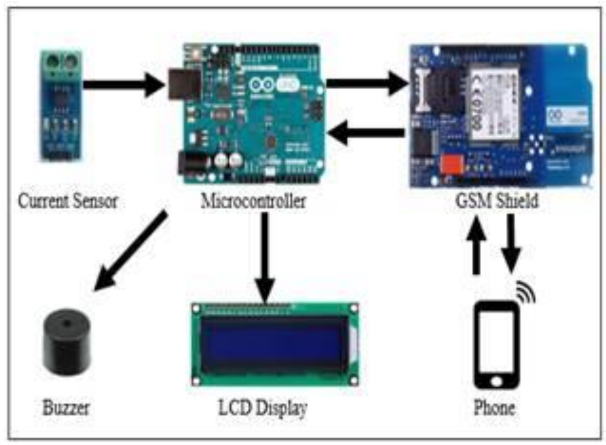

Figure 1: Overall system block diagram.

This device is capable of diverting calls automatically and replying the kWh and dollars consumed through SMS to the customer. Also, at every 30 days reset, the device sends a total consumption SMS to the utility supply. The warning feature when activated, sends a warning SMS to customer along with the beeping of the buzzer for notification of incipient faults.

3. Validation through Simulink

Before actual implementation, it is highly recommended to verify the sensors characteristic. It ensures to enhance the quality through human like decision values. We adopted Fuzzy logic decision to further improve the sensory circuit. In following subsection, Fuzzy modelling for current and voltage sensors is described to understand how it is embedded in software logic.

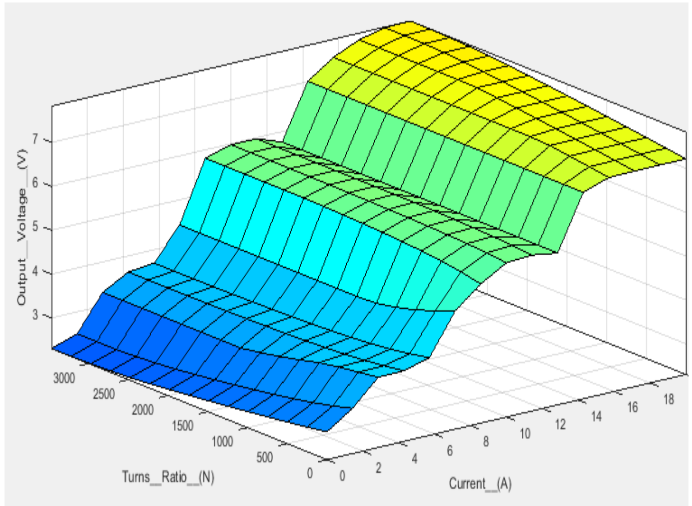

Figure 2. Fuzzy logic 3D surface view obtained through simulation of fuzzy rules/sets.

3.1 Fuzzy modelling for current sensor

The current sensor can be modelled in fuzzy logic to represent the output voltage created at varying current relative to the number of turns. Basically fuzzy logic maps an input space to the output space based on a set of *if* and *then* statement called the rules. Some of the advantages of fuzzy logic include firstly, it is conceptually easy to understand as it uses linguistic variables and it is flexible and can be easily implemented, secondly fuzzy logic can model nonlinear functions of arbitrary complexity and it provides the ease to model your reasoning. The following fuzzy rules were set to attain the nonlinear 3D surface. The surface shown in Figure 2 depicts an output that is sufficient to be read by an analogue input channel of a microcontroller. Output scenarios are defined as Low, Medium, High and Very high voltage outputs. The following rules have been applied to the model. The fuzzy logic rules are outlined in the following Table 1. The fuzzy logic rules give the relationship between current and the output analog voltage through the current sensors.

As per the fuzzy rules, when the current increases, the output voltage also increases, while the turn’s ratio remains at its maximum. In order to obtain the calibration equation from current sensor device, we obtained first the normal sensitivity and transfer characteristics of the ACS712-05B sensor and with reference voltage setting of 5VDC and converter size of 10 bits. In order to sense the voltage the count relation is established as follows:

$$N = \frac{1029}{V_{cc}}\left(\frac{V_{cc}}{2} + 0.185 \times V_{in}\right) \quad (1)$$

where Vcc represents the supply voltage to converter, Vin is the input voltage and N is the calculated count from the converter based on resolutions. It is to be noted that in practice we measure the count from the converter and estimate the input voltage using the microprocessor counting features.

Also, we have used the supply voltage equal 5V and interestingly, the final equation relating input voltage and count is remained the same even the power supply fluctuates.

$$V_{in} = 0.0264(N - 512) \quad (2)$$

The above relation is used to calculate the voltage and so to convert in current measurement using the V-I characteristics of the sensor.

Table 1. Fuzzy logic rules.

If Current_(A) is:	*And Turns_Ratio_N is:*	*Then Output_Voltage_(V) is:*
Very high	Maximum	Very high
High	Maximum	High
Medium	Maximum	Medium
Low	Maximum	Low

3.2 Energy meter model

Efforts were made to test the concept first in Simulink environment. General system architecture was modelled as shown in Figure 3 using a simplified block diagram. In the Simulink/MATLAB model the utility/grid side supply contains a 240V AC voltage source. Voltage sensor is connected in parallel while the current sensor is connected in series. A series RLC load is connected to the terminals from the grid power supply. In this system architecture microcontroller is responsible for taking input readings from the current and voltage sensors and computes the electricity consumption in kWh and the amount of electricity consumed in dollars.

There are two inputs, voltage and current from the two sensors in the main system architecture. The value oscillates from negative to positive. Hence it is changed to I_{rms} and V_{rms} to extract the positive portions only. Power is obtained in watts from multiplying the I_{rms} and V_{rms} values. The value in kW is then converted to kWh using an input clock, time. The kWh value can also be used to calculate tariff rate in local currency in dollars. Both the kWh and the consumption amount in dollars are shown on user display screen.

GSM communications is achieved through representation of customer text through the phone text messages. A request by customer is modelled by a step signal in the Simulink/MATLAB model. If a step signal is detected by the GSM communication state flow logic module, the trigger will be activated for sending the kWh and the amount in dollars to the customer represented by phone text display. The state flow chart works by detecting change in input state and providing an output state. When a message is not requested then the state is zero. In this representation, the output is true, hence the state logic is one and the trigger function is active.

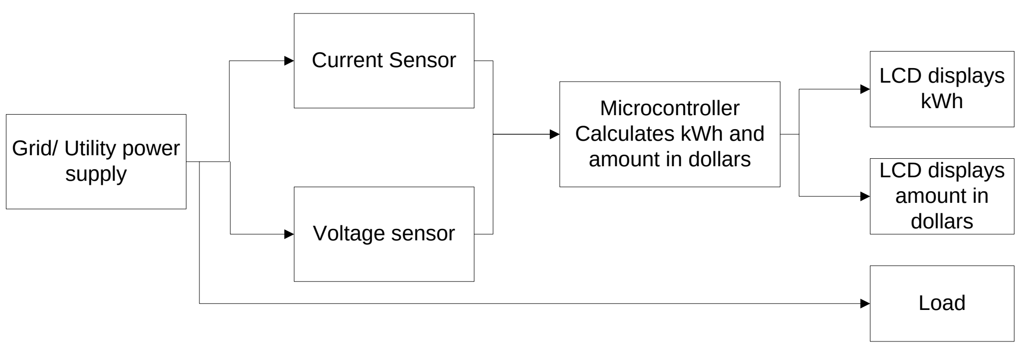

Figure 3. Operational block diagram for energy meter prototype.

3.3 Software test

To verify the operation with GSM and sensor models, we assume the voltage and current varies between ±250V and ±4A which are scaled with respect to time in millisecond. From the depicted fuzzy rule surface, we obtain the increasing values of kWh with respect to the time. As the values of current and voltage are acquired, power is calculated in kWh and also it has been accumulated. The pattern of measured power is shown in Figure 4. The graph depicts the increasing values of kWh with respect to the time. As the values of current and voltage are acquired, the power is calculated. The kWh value is then accumulated. During device implementation, the power accumulated (kW) will be multiplied with time (h) to give kWh value. The state flow logic in active and in-active scenario is shown in Figures 5 and 6. This is evident by the display of kWh and dollar values as output. Upon request as a step signal receives, the state logic updates to 1 which triggers the GSM SEND blocks. Both the blocks are then allowing the signal to pass through to the display. Similarly, state flow logic also works as inactive scenario. This is evident by the display of kWh and amount in dollars which are shown as zero. There is no request hence the state remains 0. This does not trigger the GSM SEND blocks. Hence the signal does not pass through to the display.

The fuzzy logic improves the predicted output quality. Figure 7 is presented with the sample response to see how the output behaves for nonlinear characteristic of user load demand. The output voltage with respect to time is shown. Maximum voltage of 7.5V is produced for the maximum calibrated input current. This is the model of the current sensor depicting the output voltage produced at varying real-time input current. This helps to model sensors operation at varying current intervals.

For a nonlinear load as shown in Figure 7, maximum voltage is drawn over the period of time for which the load is connected to the test system. For this test system, a maximum of 7.5V is drawn.

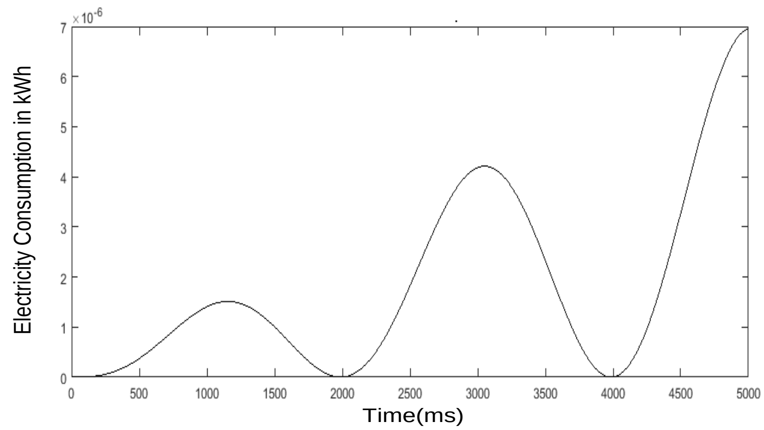

Figure 4. Electricity consumption in kWh vs time relation.

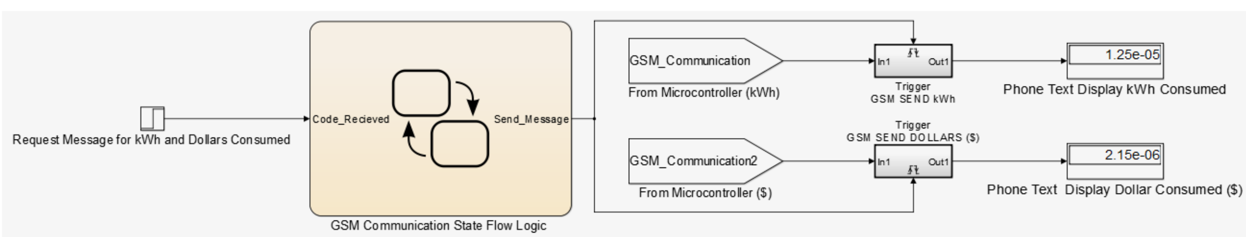

Figure 5. GSM communication state flow logic active in Simulink/MATLAB.

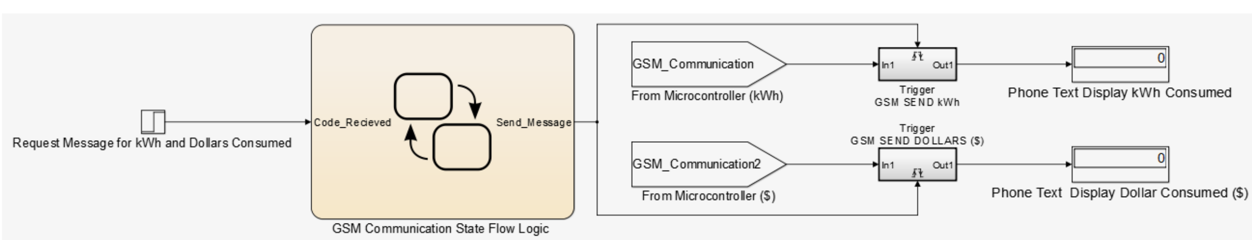

Figure 6. GSM communication state flow logic inactive in Simulink/MATLAB.

4. Hardware test and verification

Figure 8 shows the actual picture of the system, assembled with depicted objectives. The major components of the hardware are labelled in the figure. The current sensor is connected to Arduino Uno analogue input channel. A GSM shield is calibrated to operate with local mobile service provider. The display LCD is used to display the various measured quantities like, current in amperes, power in kW, kilowatt- hour (kWh), and the amount of electricity consumption in dollars. The separate battery charger has been designed for automatic charging and filtering of noises. When there is no electricity supply the backup battery activates and can communicate with user. The buzzer is used to warn the user if a critical condition occurs. In operation, it is programmed to warn the customer via SMS if the current exceeds 16A. Also, the buzzer is turned on to indicate warning. This is automatically detected as well as the system goes back to normal once the fault is corrected or the breaker trips. Apart from the safety feature of the system, normally the customer can get the power usage information automatically via a simple dial a call. In fraction of a second, the user will receive the message (as shown in sample test Figure 9) stating the power consumed in kWh and charges in dollars. Also, the device is programmed to send the customer a full consumption for one month period.

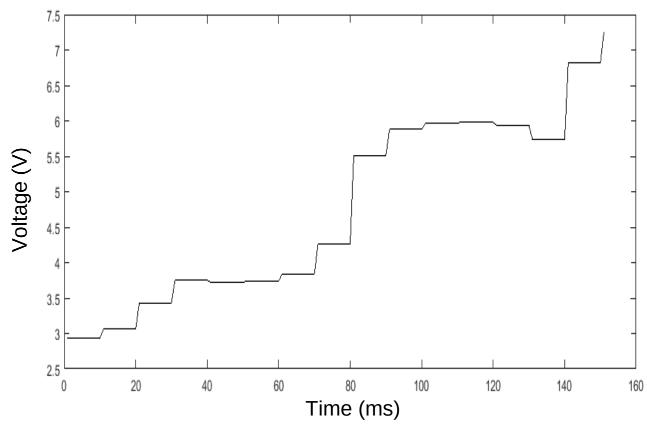

Figure 7. Fuzzy based decision output in the form of voltage vs time relation.

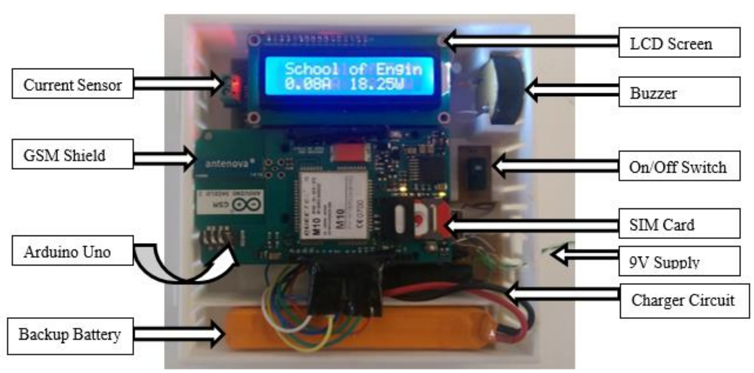

Figure 8. Hardware prototype of digital energy monitor.

4.1 Validation through comparison with a calibrated device

Experimental load setup was made with various demand conditions. To evaluate the current sensor measurement, we have used a calibrated meter as a reference device and measured the output current (I_{rms}) values for 95 minutes continuously. Load was varied (turned on/ off) at five minute intervals and the measured current was drawn into load by using the prototype and calibrated reference meter in series. The obtained results are plotted in Figure 10. It has been noticed that only 3% error is introduced with firstly calibrated sensor. However, it can be eliminated by sensor modelling equation which is implemented in central processing unit.

One of the protective features incorporated was the warning system. This device also has a retrofit-able design inducing portability. Instantly when requested, the customers can get their real-time energy consumptions. Also, warning messages can lead to better precautionary measures during electricity disturbances in the household. In the testing phase, it was evident that the presented result has the closer outcome to the standard devices available in the market.

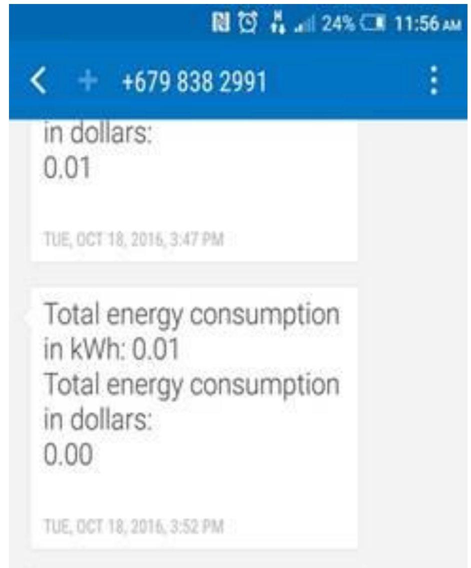

Figure 9. SMS text to customer.

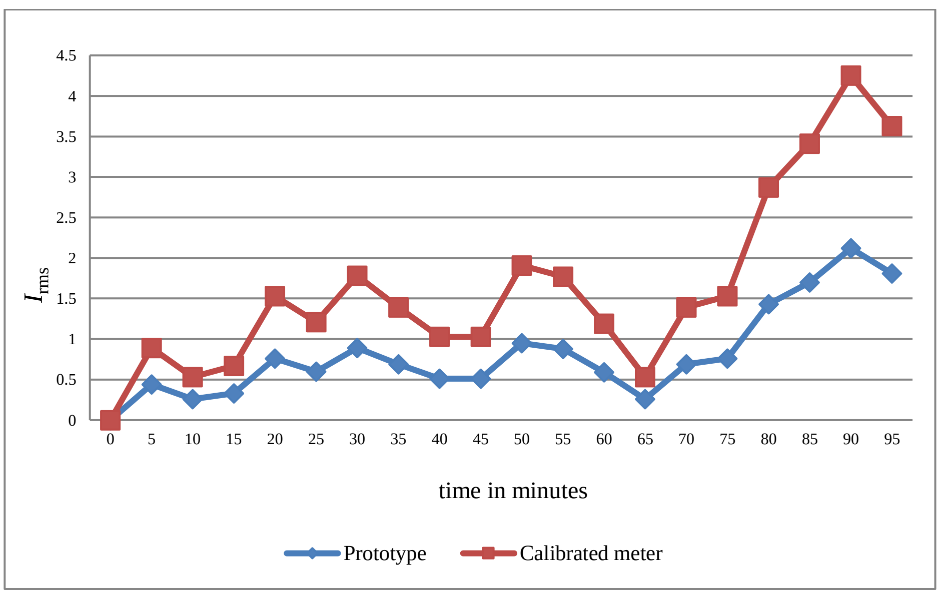

Figure 10. Comparison of prototype device with calibrated meter.

5. Conclusions

This paper has described the design of a user friendly and adoptable digital energy meter. The efforts are made to describe the working of sensors and communication strategy in the simulation environment. It is proved how the fuzzy logic controller changes the performance of the smart monitoring. The actual prototype device was fabricated with support of central processing unit. It has the GSM shield inbuilt for communication with existing mobile networks. The prototype turned out to be feasible, user friendly and cost-effective. Thus, we can see that the result is most beneficial to the utility and as well as to the customers across the pacific island countries. For future work, research is still needed to understand the utility and automatic load control applications. Tariff information can also be handled via remotely; enabling one to use the better planned data, budgeted and informed customers.

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