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Design and Implementation of a Cloud Based Energy Monitoring and Control System for Demand Response

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ABSTRACT

In recent times energy policies have focused on migration to a low carbon economy to curb the adverse effects of greenhouse gases. This has favoured the adoption of renewable energy sources such as solar and wind energy which are increasingly being installed in large capacities. The intermittent and seasonal nature of renewable energy sources however presents a situation which requires a modification in the way the electricity grid is controlled. This has given rise to novel research in demand response; a component of the smart grid which leverages modern information and communication infrastructure available to implement a power grid where the consumer plays a more active role than in the conventional grid. This paper draws inspiration from this novel concept to present the design and implementation of a cloud-based energy monitoring and control system for demand response in which energy consumption can be monitored and controlled remotely via the internet.

Key Words: *Energy, Demand-Response, Smart-Grid, Telemetry, Internet of Things.*

1.0 INTRODUCTION

Energy is a very important resource which is directly linked to human economic activity and as such, the conservation and efficient use of energy is required to avoid waste. Significant energy reduction has been required in all areas in order to address current energy crisis while the demand of energy on the other hand is on the increase as more appliances are being installed [1]. Another cause of concern in this area is the coming of plug-in hybrid electric vehicles which are known to significantly affect the power distribution system due to their charging rate [2]. A means of balancing the increasing demand with the supply is required in order to maintain a reliable and uninterruptible supply from the grid. This has been done traditionally from the supply side by constructing new generating units to match the maximum demand of the system [3]. This method has the obvious disadvantage of having generation capacities installed only to handle the peak demand of the system which only occurs at certain periods thus sinking capital investments which would not be in use most of the times. Figure 1 shows typical load curves with the peak occurring only within certain hours of the day.

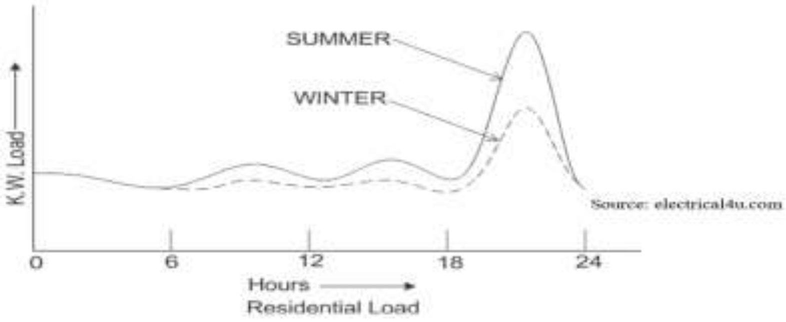

Figure 1: Typical Residential Load Curve

A strategic way of handling this problem in an era where more renewable energy resources are being introduced to the grid is the introduction of demand response or demand side management and the smart grid [2]. The smart grid as opposed to the conventional grid leverages on existing techniques such as automation, information and communication systems to monitor and control the loads connected to the grid [2]. Demand response on the other hand being a component of the smart grid refers to the modification of electricity consumption patterns by the consumer in response to incentives or signals from the utility service provider which communicate price or grid reliability issues [4]. This provides a means of balancing the supply and demand by optimizing power resources in accordance to the price and reliability signals exchanged [5]. Several methods can be used to implement demand response. These include; peak clipping, valley filling, strategic conservation, strategic load growth, load shifting and flexible load shape. To implement any of the aforementioned demand response techniques, a means of monitoring the load is required as well as a means of controlling the consumption to achieve the objectives of demand response.

An energy management system is a system used to monitor, control and optimise the use of the electricity grid. Smart home has been identified as one of the applications of smart technologies in residential buildings that can help improve energy management and curb waste and carbon emissions [6]. A home energy management system (HEMS) therefore plays a key role in the efficient operation of home appliances coordinated by load management in line with residential demand response strategies [6]. For this reason, Ahmed et al [6] applied Artificial Neural Network with Lavenberg-Marquardt training to the Home Energy Management Controller considering demand response events in which four HVAC loads were simulated in Matlab/Simulink. This was done to automate the responses to demand response (DR) signals and thus manage the power consumption in order to reduce electricity bills.

Devi & Ayswarya [2] in a similar vein presented an autonomous demand-side energy management to encourage users to willingly modify their electricity consumption without compromising service quality and customer satisfaction using load forecasting. This system provides a means for the electricity consumer to automatically optimize electricity usage using a neural network trained with data of normal electricity usage in a typical residential building.

Madhubabu & Sekar [1] designed and prototyped an Xbee and GSM based wireless smarter home energy management system using an ARM7TDMI microcontroller for local processing alongside an LCD screen for displaying measured parameters and a pair of Xbee radio modules for wireless transfer of measured parameters to a remote computer for display. The design also featured the use of a GSM module for communication and control through the internet.

Palacios-Garcia et al [7] developed and implemented a laboratory scale version of an energy management system using smart meter data for energy management operations and power quality monitoring in a micro grid. The system developed by [7] involved the use of a smart meter with a link to a computer and a web service for power quality monitoring. Labview was used to develop the monitoring and display interface used in the system.

In the subsequent sections of this paper, the design of a monitoring and control system for demand response is presented in which the processing of all monitored data is done on a remote server resident in the cloud. This system also provides a means for remotely controlling the loads connected to the system which could either be turning on or off as the case may be to implement one or more of the objectives of demand response. Furthermore, we present the design and configuration of a radio network and internet gateway device used to link the energy monitoring and control system to the cloud-based server on the internet. An Xbee/Zigbee radio device is used as a standalone wireless microcontroller device which interfaces both the sensor side and the radio side of the system. This architecture, unlike those previously mentioned does not employ an additional microcontroller thus reducing the overall component count of the system. This could as well be deployed on a large scale leveraging the mesh networking ability of Zigbee devices which could be employed by the utility service provider or the consumer as the case may be.

2.0 METHODS

2.1 Monitoring/Control Circuit Design

The design of the cloud-based measuring and control system for demand response was done according to the block diagram presented in Figure 2.

Figure 2: System Architecture of the design

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2.2 Power Supply

The sensors and actuator circuits are powered from a linear voltage regulator connected to the potential transformer used to step down the mains voltage. The Xbee/Zigbee device is powered from a 6V battery pack supplied with the Xbee cloud kit development board. The gateway device used is the Digi Xbee gateway device which is powered from a separate power pack supplied with the gateway device and cloud kit development board.

2.3 Voltage Signal Conditioning Circuit

The voltage sensor conditioning circuit consists essentially of a full bridge rectifier, a filter capacitor and a potentiometer. The potentiometer is used to set the voltage at the required level for the A/D converter of the Zigbee device. A filter capacitor capable of handling the ripples was chosen to significantly filter out the ripples in the voltage fed to the A/D converter. The expected mains voltage for the system is 240V single phase voltage. For this reason, a 240V/12V step down transformer is used to step down the mains voltage to a level which can be handled by the electronic components. This also provides isolation of the AC mains voltage from the DC voltage used to power the on board electronic devices. The full bridge rectifier converts the AC into a DC signal suitable for the A/D converter. Figure 3 depicts the circuit used to process the measured voltage signal. P1 in Figure 3 denotes the ADC pin used for voltage measurement on the Xbee device.

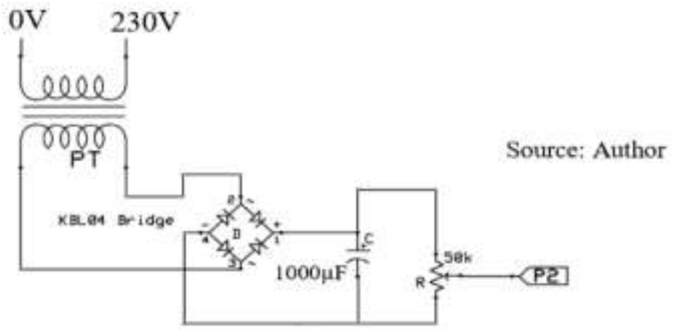

Figure 3: Voltage Conditioning Circuit

2.4 Current Signal Conditioning Circuit

To measure the load current, a current transformer is used to convert the load current into an equivalent voltage level suitable for measurement. This is shown in the circuit schematic of Figure 4. The transformer used is a 1:1000 turn ratio current transformer from Triad Magnetics. The voltage obtained from the secondary of the current transformer is fed through a half wave precision rectifier (Figure 4) which converts the AC signal into a half wave DC signal. This DC signal is filtered appropriately and scaled to a range which can be processed by the A/D converter of the Xbee. A precision rectifier or "super diode" consists of an operational amplifier and a diode rectifier. This is employed in this design due its ability to practically eliminate the 0.7V or 1.4V barrier voltage introduced by a half or full bridge rectifier which would introduce a large error in the measured value of the current if employed in the current signal conditioning circuit. The potentiometers are used to set the signal at the appropriate level. The amplifier gain is set to unity by the 3.3kΩ resistors as shown in Figure 4. The 5.1kΩ resistor recommended by the data sheet of the current transformer serves as a shunt resistor which is similar to what is obtainable in moving coil ammeters. P1 in Figure 4 denotes the ADC pin of the Xbee device used for measuring current.

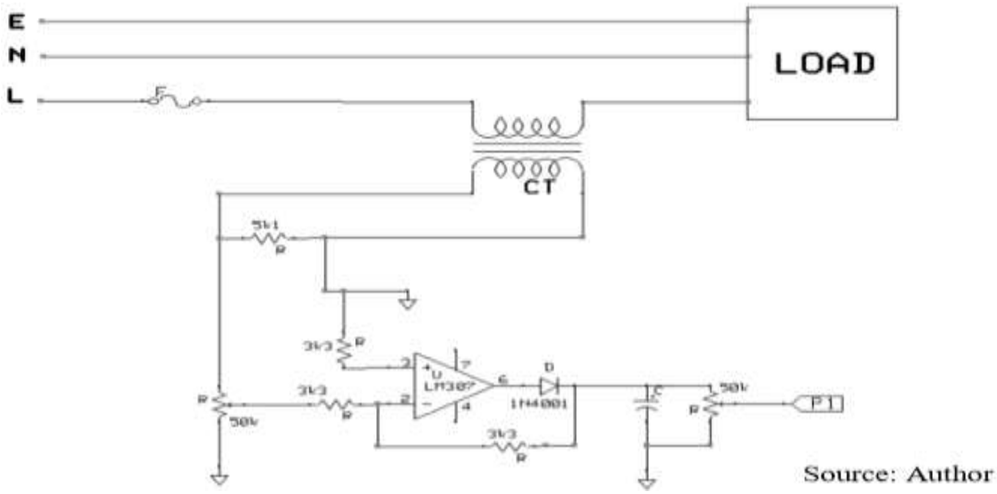

Figure 4: Current Signal Conditioning Circuit

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2.5 Actuator Circuit

The actuator circuits designed to turn on or off the loads are transistor driven relay circuits powered from a 12V power source as depicted in Figure 5. The transistors used are NPN transistors whose base limiting resistors have been chosen as 10kΩ to limit the saturation current. An on/off manual control is implemented in this case as demand response algorithms and policies are still in the development stage. This leaves an opening for future automation algorithms which could be implemented in the system. P3 is a digital I/O on the Xbee designated for sending out actuation signals to the actuators.

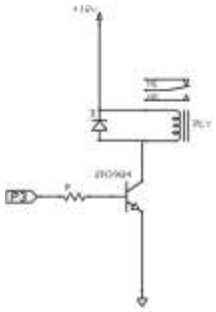

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Figure 5: Actuator circuit

2.6 Circuit/Cloud Interface

The circuit/cloud interface consists of two networks; the Xbee to gateway RF network and the gateway to internet network. The Xbee to gateway RF network consists essentially of one or more Xbee devices in the field which measure the energy consumption parameters and transmit such to the gateway device. The gateway to internet network consists of the gateway device and a wireless router which is hooked up to an internet server. This network receives the data from the Xbee network and sends it to the internet where further processing is carried out in a cloud-based server. The gateway device used in the implementation of this network is a Digi Xbee gateway device which is used to link one or several Xbee devices to the internet/cloud platform.

2.7 Network Configuration

It is necessary to configure the network so that data can be transmitted from the sensors to the internet platform for processing, monitoring and control of energy consumption. The network is configured by first configuring the Xbee device to link up with the gateway device. Three parameters are essential in the configuration of the Xbee device which are; the Personal Area Network address (PAN), the 16-bit networking address (unique to each Xbee device) and the radio settings which determine the range of the device. In this setup, the PAN address was the only parameter entered as the 16-bit networking address was assigned by the configuration software (XCTU) by default. The radio settings were all kept at the default settings. The PAN address in this case was chosen arbitrarily as 0x267 and written to the Xbee device in the AT mode via the USB port of the computer running XCTU.

For the Gateway to be able to retrieve data from the Xbee and send such to the internet via the Wi-Fi network, the Gateway must be configured to connect both to the internet and to the Xbee. The gateway is allowed to create a wireless network (xbgw-00:40:9D:81:39:71) to which the computer is connected. Using the network already established, the IP address *http://192.168.100.1* is entered into a browser in order to access the configuration page. This network is disconnected after the configuration in order to connect to the Wi-Fi/internet network.

To configure the Gateway, the serial number of the Gateway and the Xbee RF module address are written down and entered into a web page configuration interface. This configures the gateway and Xbee device and an online widget can be created subsequently for monitoring and controlling the energy consumption on the Digi Cloud Kit Heroku website.

2.8 Calibration/Online Widget Configuration

In order to ascertain the magnitude of the physical quantity being measured, a means of calibrating the instrument is required. This involves determining the counts corresponding to a certain magnitude of the voltage or current as the case may be. In this case, the counts per volts corresponding to 1LSB (Least Significant Bit) for the voltage meter is presented in equations (1), while that for the current meter is presented in equation (2).

$$1LSB = Count\ per\ volt = 10232 = 515.5 \approx 516\ (per\ volts) \qquad \ldots 1$$

$$1LSB = Count\ per\ volt = 7730.895 = 863.7 \approx 864\ (per\ volts) \qquad \ldots 2$$

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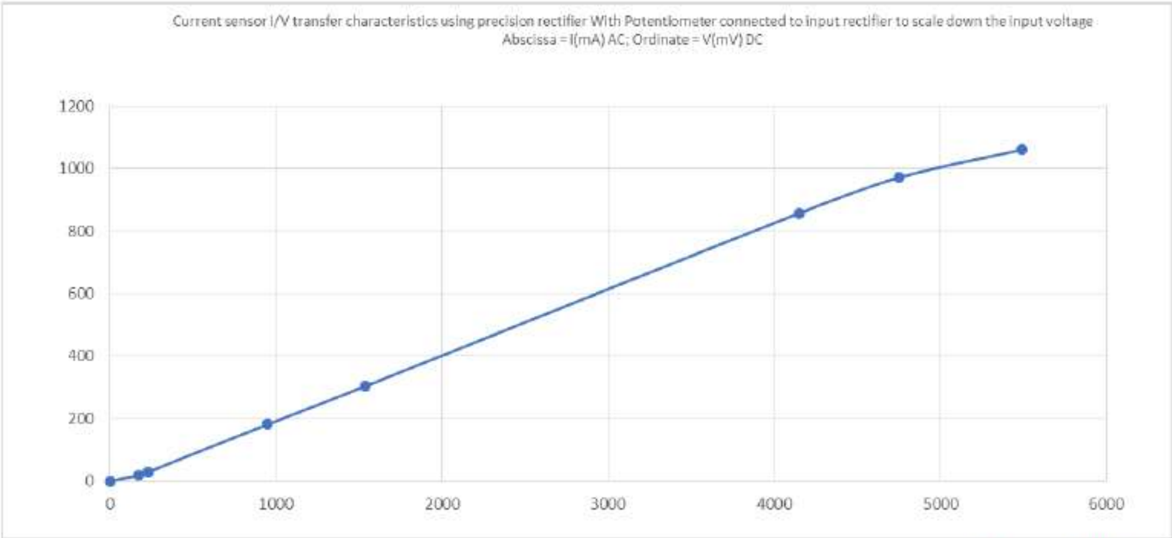
Furthermore, a scale ratio is introduced. The scale ratio represents the magnitude by which the voltage or current has been reduced in order to meet the requirements of the AD converter. This value is incorporated in the final computation of the measured parameter. Since a 36V AC source was used in the experimental setup the maximum analog voltage input for the Xbee is 2V, it implies that the scale ratio for the voltage sensor is 2/36V while that for the current was set as 1 as a result of the magnitude not being up to 2V. The formula for computing the measured voltage is presented in equation (3).

$$V = \frac{Value}{1LSB} \div scale\ ratio = \frac{Value}{1LSB \times scale\ ratio} \qquad \ldots 3$$

In order to measure the current, a transfer characteristic (shown in Figure 6) which matches the current sensor output voltage to the magnitude of the current measured was derived from testing and subjecting the sensor to various loads. The slope of the graph was computed as 0.212Ω. The current magnitude is obtained by dividing the sensor output voltage by the slope of the transfer characteristics which in this case is 0.212Ω.



Source: Author

Figure 6: Calibration Graph of Current Sensor.

The formulae derived for the sensors were all entered into the online application widgets which display the measured parameter in graphical form in a gauge like manner as shown in Figure 8. The formula for the energy measuring widget is simply the product of the voltage magnitude and the current magnitude. The phases were not considered as the loads used to test the system were all resistive loads and the use of reactive loads was not included in the scope of this work.

As earlier stated, the control method implemented was an "on-off" control which enables a user of the system to turn on or off a particular load from the consumption information displayed in the gauges. Widgets in the form of buttons were configured to send a signal to the control terminal in the field on clicking the control buttons on the screen as depicted in Figure 8.

All online widgets have been preprogrammed using JavaScript, CSS and HTML by Digi International and hosted on the Heroku GitHub website. Editing the source file for the online application is restricted while any user may configure any of the preprogrammed widget applications to suit the users' application. In this work, the default JavaScript, CSS and HTML codes were used.

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3.0 RESULTS

The test rig for the cloud-based energy monitoring and control system was set up as shown in Figure 7.

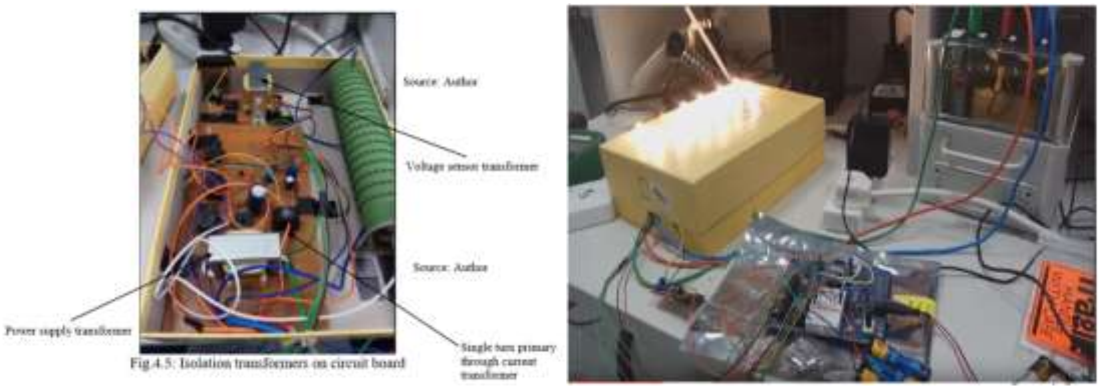

Figure 7: Physical Implementation of the System

In this setup, three (3) sets of loads have been used to test the system; two groups of six (6) lamps rated at 12V/100mA with an uncertainty level of ±100mA and a power resistor rated at 200W/10Ω (the power resistor in green and the lamps lit as shown in Figure 7). The loads were monitored using the online widgets setup as depicted in Figure 8. The loads were monitored over a radius of 30m from the IP gateway around the building. This is within the indoor range of the Xbee as specified in the datasheets. Table 1 presents a summary and comparison of the measurements taken and the values obtained by analytical computations from datasheet values.

Figure 8: Online Dashboard showing Widgets and Measured Values

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Table 1: Summary and Comparison of Measured Values with Datasheet Estimates

S/No.	Load	Metered Current (mA)	Calculated Current based on Datasheets (mA) (Error = ±10%)	Current Range based on datasheets specification (mA)
1.	Lamps_1 only	459	500	450 – 550
2.	Lamps_1 & Lamps_2	1157	1100	990 – 1210
3.	Lamps_1, Lamps_2 & Heater	4930	4700	4230 – 5170
4.	Lamps_1 & Heater	4406	4100	3690 – 4510
5.	Heater	3811	3600	3240 – 3960

4.0 DISCUSSION

Of the various load shapes desired for energy management, peak clipping and load shifting are the most applicable and relevant to energy efficiency [8]. In view of this, the cloud-based energy monitoring and control system is suitable for peak clipping; a condition in which the loads are turned off to prevent them reaching the peak. This can be adapted to a building as depicted in Fig.5.8. In this building plan, a monitoring device is placed at each Distribution Board to monitor the consumption of the individual circuits connected to the Distribution Board. Heating Ventilation and Air Conditioning (HVAC) loads alongside other high-power devices would be the subjects of the monitoring and control system as these are most often the target for Demand Response (DR) events. With the Xbee/Zigbee devices, a star network topology can be implemented in a building where the Gateway device is central to the monitoring systems and serves as a network hub. Also, other network topologies such as mesh or tree topologies can be implemented for larger networks. This would ensure reliable routing of data as fault tolerant networks can be built upon these topologies. The monitoring and control system could also be deployed at the outlet supplying a load and not necessarily at a Distribution Board of a building. As the test carried out reveals that communication is possible within a range of about 30m, it is recommended that the device be setup within this distance. Exceeding this range might affect the reliability of the system.

Where the distance exceeds 30m which could be in a large or high-rise building, a mesh networking scheme may be adapted since the Zigbee network protocol makes provision for mesh networking. This would extend the coverage distance of the monitoring and control device. With a mesh arrangement, a Direct Load Control (DLC) program could be implemented by the utility provider where the utility provider could remotely turn on or off certain consumer HVAC loads on short notice. This could employ a Gateway device with a capability to connect to a nearby cellular network such as that produced by Digi International.

Having tested the system, some appreciable delays in updating measured parameters to the online dashboard was observed. This obviously is the result of latencies in the network which could either be from the speed of the internet connection or from the traffic encountered at the online service provider end. For applications where time is of the essence, it is recommended that such a system be built around a very fast internet network connection for better performance and service providers which use the MQTT protocol might prove to be a better option as this has reduced data packet overheads thus increasing network speed [9].

5.0 CONCLUSIONS

This paper has presented a study of demand response as it relates to energy management. Various methods of implementing demand response which include load clipping and valley filling among others have been highlighted and load clipping has been identified as a practical means of implementing demand response. In order to achieve the aim of demand response, an energy monitoring and control system has been designed and developed to implement load clipping. This design takes advantage of the ubiquitous nature of the internet to implement a cloud-based monitoring and control system for demand response. In this design, all computations are carried out in a cloud-based server. This makes the monitoring and control system accessible from any computer connected to the internet and can thus be monitored and controlled from any location with an internet connection.

A Zigbee device has been used in this design to implement a wireless network from the remote sensor to the monitoring terminal. This has an obvious advantage in the sense that it offers a means for network expansion and reliability as a ZigBee mesh network could be designed and implemented to accommodate several remote sensor/monitoring devices and the data from one device can be re-routed in case of a failure somewhere in the network.

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Furthermore, a practical means of deploying this system in a building has been proposed based on the range of the Zigbee/Gateway devices used in the system and practical ways of improving network speed and reliability have also been highlighted.

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