Smart Home

Energy Management System for Demand Side Mangement

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With South Africa's energy grid currently under severe pressure due to a lack of planning, electricity prices have escalated. This has forced consumers to look toward finding innovative ways to reduce their consumption.

The aim of this research project was to create a system that assists in the reduction of household power consumption by simplifying the process of power saving. This is done by enabling consumers to remotely monitor and control their household devices.

To achieve this goal, a power management system was designed that consists of a Beaglebone black, the main electronic controller, and a circuit for measurement and control. The measurement circuit measures the power consumption, it is then sent to Trintel's SMART Platform enables users to remotely monitor and control the devices by using a web-based interactive graphical user interface.

I. INTRODUCTION

In the last decade South Africa's energy demand has significantly increased. This trend is not just confined to just South Africa but is a global one. As we entered the technological era, the amount of devices that require electricity increased immensely and this has put a big strain on the electric utility, in South Africa's case Eskom. To get ahead of this growing demand Eskom is trying to increase its capacity by building new power plants as well as operating their existing plants uninterruptedly. Another strategy which has been adopted is to put old "mothballed" plants back into operation at a very high cost. As a result the cost of electricity has increased and will continue to do so if the growth in power usage is not regulated.

Because of the continual increase in the demand for electricity and the utility's relatively static capacity to generate it cannot be reached. The relatively static capacity is mainly due to the lengthy lead time that it takes to increase infrastructure as well as the lack of capital. Fortunately there is now a constant drive towards a more sustainable society that seeks to reduce the per capita energy need. Utilities can take advantage of this intent by incentivizing the reduction in energy use and in doing so create spare capacity and buy time before new plants come online.

The main influencing contributes to energy usage levels in an average household are its geyser, stove, heating appliances, pool pumps and lights. In order to get South Africans to reduce their energy usage Eskom have launched numerous campaigns such as the 49m [1] initiative to create awareness and inform the public on how to reduce energy consumption. The impact of these campaigns, however, has not been very successful as it depends solely on the user's willingness to change established habits and routines and make lifestyle adjustments.

The concept of this project came from Eskom's Integrated Demand Management Program (IDM). IDM was created to ensure the security of electricity supply by optimizing energy use and balancing electricity supply and demand [2]. During times of high demand the energy grid can become unstable and deviate from the operating frequency of 50Hz. In order to avoid this, Eskom runs backup jet turbine generators at a very high cost to maintain system integrity. This project applies the IDM program's concept to the general public by encouraging consumers to use less electricity by incentivizing every kWh of electricity they save, affording users the opportunity to conveniently control their household energy consumption.

Two factors that are important for a system that will help manage the energy consumption of households is its ease of use and non-intrusiveness, so as to increase the willingness of consumers to participate. Curbing electricity usage will save the user of this system money, which will double as an incentive for consumer participation as well as having the desired effect of decreasing electricity demand.

II. HISTORY OF SOUTH AFRICA'S ENERGY SECTOR

South Africa's electricity needs are dominated by Eskom, a state-owned public utility, which supplies approximately 95% of South Africa's electricity [3]. Its total generating capacity comprises a total net output of about 41GW [3]. When the fully democratic government came into power in 1994 they embarked on an ambitious programme known as Reconstruction and Development Programme or RDP. One of the goals of this programme was to provide electricity to all homes. Between 1994 and 2000 around 1.75 million extra homes were connected to the grid [4]. The 1998 White Paper on the Energy Policy of South Africa stated that the "growth in electricity demand was to exceed the generation capacity by approximately 2007" and that "long capacity-expansion lead times require strategies to be put into place" [5]. Unfortunately the new government also attempted the privatisation of the

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electricity sector in the late ’90s and as a result it denied Eskom’s request to build new power stations in 1998. No further base-load stations were built and from early in 2006 the grid was regularly crippled due to a lack of generating capacity that lead to widespread blackouts due to load-shedding [6]. The president of South Africa finally confessed in 2008, “When Eskom said to the government: ‘We think we must invest more in terms of electricity generation’… We said not now, later. We were wrong. Eskom was right. We were wrong.”[7]

Notwithstanding the president’s confession, the government and Eskom was severely criticised for not being able to prevent the energy crisis As a result Eskom embarked on an extensive Demand Side Management programme to reduce energy consumption. This included the distribution of more than 30 million CFLs between 2007 and 2010 [9] and funding the installation of geyser blankets to reduce heat loss, covering nearly 180 000 hot-water cylinders during 2006 in the Western Cape alone [10]. Incentives were also offered to consumers to replace stoves and geysers with gas and solar-powered versions [11]. By 2010 these interventions realised total demand savings of 2 372 MW during evening peak time, when compared to 2003 consumption [12]. By the end of 2013 Eskom’s GM for integrated demand management (IDM), Andrew Etzinger, claimed that “the interventions had made a material difference in the country’s power situation. With verified savings of about 3 600 MW since inception, the IDM programmes have established capacity equivalent to that of an average power station.” [13]. Unfortunately the end is not yet in sight with Eskom stating as recently as November 2013 that “South Africa’s power supply is stable but remains tight” [14]. This situation is set to continue until at least 2017 when two new coal fired power stations, Medupi and Kusile, each with a capacity of 4 800 MW, is expected to be completed [15].

In recent years Eskom also had to endure increased criticism due to its reliance on non-renewable energy sources such as coal. South Africa is a sunny country that offers excellent opportunities for solar power. According to the Department of Energy, South Africa’s annual 24-hour global solar radiation average is about 220 W/m^2 versus about 100 W/m^2 for Europe [16].

South Africa is in desperate need for economic growth to fight the high prevalence of unemployment, some arguing for growth as high as 8% [19]. To accomplish this, high growth in energy generation capacity will be needed. An immediate net growth in the available power can be realised if consumers further cut back on their consumption. Two of the most important ways to realise this are by using more efficient appliances and employing technology to spread the power demand more evenly. A Smart energy management system will definitely help to realise this goal.

III. SYSTEM DESIGN OVERVIEW

A. *Complete System Overview*

The system consists of four main parts, namely the Smart Platform, modem, Beaglebone Black and the Power Measurement Circuit (PMC) as illustrated in Fig. 1. The objective of this system is to enable a user to remotely monitor a household’s power consumption and then switch different zones/appliances within the household on or off in order to reduce power consumption. The Beaglebone Black is the heart of the system as it plays the role of the Main Electronic Controller and handles all the communication between the different parts.

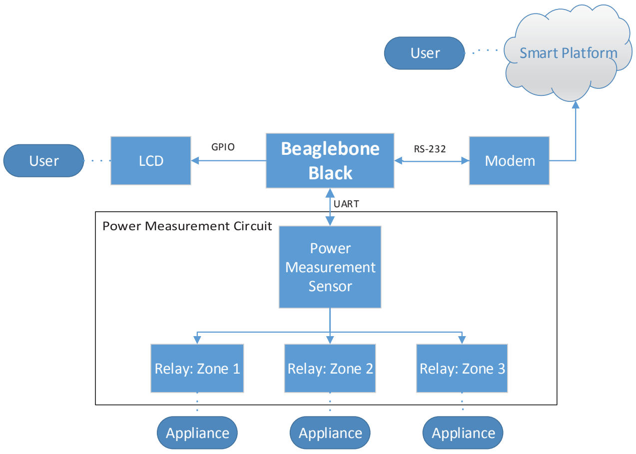

Fig. 1: Complete System Diagram

The functioning of the system can be described as follows: The power measurement sensor measures the supply voltage and current drawn by the connected load. The Beaglebone Black in turn requests a reading of the power drawn by the load from the sensor every 10 seconds. The Beaglebone Black then calculates the energy consumption per hour as this gives a much clearer understanding of how much energy is being consumed rather than just instantaneous power usage. This data is then processed by the Beaglebone Black and sent to the Smart Platform using the Sierra Wireless modem.

The user can view the data on the Smart Platform and depending on how high the power consumption is, can make an informed choice on what actions to take. Two zones/appliances can be controlled remotely from the platform by clicking on a button that sends a command back to the BBB which triggers a relay that switches off the zone/appliance or device that is connected to it.

B. *Communication System Overview*

Fig. 2 shows how the communication between the BBB, modem and power sensor is achieved.

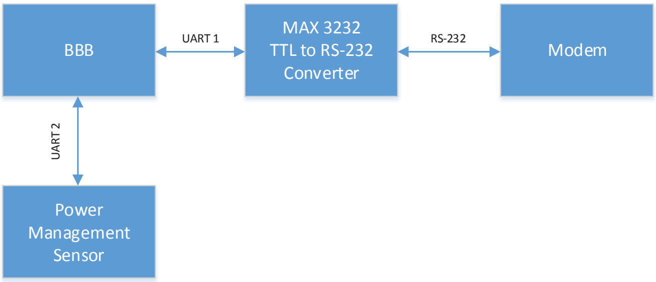

Fig. 2. Communication System

Communication between the BBB and the Modem and between the BBB and Power Sensor uses the UART protocol. Communication to the power sensor is relatively simple as both the devices have UART functionality and a direct connection could be made. The modem on the other hand communicates using the RS-232 standard. As the BBB operates at a 3.3V TTL level, a converter was needed to ensure reliable and safe communication.

C. *Power System Overview*

Fig. 3 shows the components and layout of the power sensor.

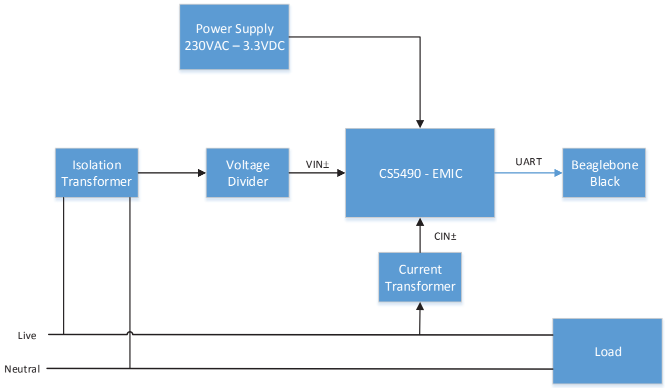

Fig. 3. Power System

The heart of the power sensor consists of the CS5490 EMIC (Energy Measurement Integrated Circuit). As the CS5490 needs a 3.3V supply voltage, a converter was designed to convert the 230VAC to 3.3VDC. For the CS5490 to accurately calculate the power consumption of a device it needs a reference voltage and reference current supplied to and drawn by the load. An isolation transformer and Voltage divider was used to supply the reference voltage and a current transformer was used to supply the reference current.

IV. PRINTED CIRCUIT BOARD DESIGN

Two Printed Circuit Boards (PCB) were designed using Altium Designer, namely a cape for the Beaglebone Black and a power measurement circuit.

A. *Beaglebone Black Cape Design*

To communicate between the Beaglebone Black and the modem the 3.3V TTL logic levels of the Beaglebone need to be converted to RS-232 levels. For this purpose a cape was designed for the Beaglebone to simplify connections and improve reliability. The cape connects to the Beaglebone Black with two 46 pin headers and the modem connects to the cape via a RS-232 connector. The main components incorporated in the cape are as follows:

- MAX3232 Logic Level Shifter
- LCD screen
- RS232 connector

As mentioned earlier the BBB communicates via UART and this method of serial communication is also known as TTL serial communication. This type of communication transmits one bit at a time at a certain data rate (in this case 9600bps). TTL levels will always remain between the limits of the microcontroller, namely 0V and VCC, and in the case of the Beaglebone these limits are 0V and 3.3V where 0V represents a logical 0 and 3.3V a logical 1. RS-232 serial communication works the same as TTL serial signals as it also sends one bit at a time at a certain data rate. The difference lies at hardware level. The RS-232 standard has a logical high at a negative voltage between -3 to -25V and a logical low at a positive voltage between +3V to +25V. The reason for these higher voltages on the RS-232 signal is to make it less susceptible to noise and also allows it to travel longer physical distances than the TTL signal [20].

In order to achieve this, a MAX3232 IC was used on the cape. This IC converts the RS-232 signals to TTL and vice versa while also protecting the transmitter outputs and receiver inputs against voltage spikes as high as 15kV.

The LCD screen was included on the Beaglebone cape initially to simplify debugging and coding but was later used to show real-time energy consumption measurements as well as voltage and current readings. This enables the user to get most of the crucial information on site without needing to connect to the internet.

B. *Power Measurement Circuit Design*

In order to make installation easier the power measurement circuit was designed that would be able to power the system, take measurements as well as to switch the loads connected to it on or off. The main components incorporated on the power measurement circuit are as follows:

- AC to DC converter
- Voltage Regulator
- Energy Measurement IC
- Isolation Transformer
- Optocouplers

To power the system a 3.3V and 5V DC power supply were needed to power the Energy Measurement IC and the Beaglebone Black respectively. An AC to DC converter was used in conjunction with a voltage regulator to convert the 220VAC from the mains to DC voltages for the system.

The Energy Measurement IC (EMIC) was chosen as it calculates power consumption using only a reference voltage and current. The power consumption data can then be read from the IC's internal registers by means of UART communication [21].

As mentioned above, the EMIC needs a reference voltage to calculate the power consumption. This can be acquired by using a voltage divider circuit. This technique is effective but can be dangerous for the user and the EMIC as high voltages are connected to the voltage divider circuit. Should something go wrong it would break the EMIC. To prevent this from happening and to isolate the circuit from the high voltage AC lines an isolation transformer was incorporated into the design.

Further protection circuitry came in the form of optocouplers. These components were used to obtain electrical isolation between the Beaglebone Black and the Power Measurement circuit. This isolation helps to protect the Beaglebone Black from voltage spikes and grounding faults as the device is especially vulnerable to external voltages when it is powered down.

V. SMART PLATFORM

To enable users to remotely communicate with and control the device a cloud platform service was setup. The Sierra Wireless Airvantage platform is a cloud platform service that allows service providers to build wireless Machine-to-Machine (M2M) applications [22]. This platform is used by Trinity Telecomms (Pty) Ltd to power their Trinity SMART platform and enable users to remotely monitor telemetry devices.

The setup of the Smart platform consists of two parts, the asset model setup and the Metric model setup. The asset model setup is used to create the asset and define its characteristics by defining its variables, events, alarms and commands. The AirVantage Configuration tool is used for this setup.

Once the asset model was created, the metric model setup could be completed. This allows the conversion of raw data coming from the asset to user understandable information that is displayed on the platform.

The Trinity SMART platform can be used to create a graphical user interface called a dashboard. This dashboard can be designed by the user to display data from telemetry systems on various graphs and meters called gadgets. The dashboard can also be equipped with buttons to send commands or data to the asset (telemetry system) [23].

The dashboard that was designed for this project can be seen in Fig. 4. Final Dashboard Layout

Fig. 4. Final Dashboard Layout

This dashboard receives five sets of data, namely voltage, current, power, energy consumption and energy savings. The power and energy measurements are displayed in a digital format as it gives the user the most accurate readings while the voltage and current are displayed on gauge scales to appeal to the general public by making the information more visually stimulating to the consumer. The dashboard also consists of three toggle switches, namely Reset, Relay 1 and Relay 2. These switches are used to send commands back to the BBB. The reset switch is linked to the Energy measurement field. As energy usage is power consumption integrated over time it needs a starting point in time. The Reset button gives a command to the BBB to restart the energy consumption calculation. The energy savings are also calculated by integrating the difference between the current power measurement and the previous. Further details will be discussed in section VI. Relay 1 and Relay 2 are used to send a command to the power measurement circuit to switch the respective relays on or off. Another relay switch could be added to the dashboard as the hardware made provision for three relay switches to control the devices' power supply

VI. SOFTWARE DESIGN

A simplified version of the main control loop for the system is shown in Fig. 5.

This control loop consists of an infinite while-loop that waits for certain events to take place. Within every cycle it checks if a command has been scheduled from the platform and if a positive result is found it determines what command has been sent and then executes that command. The rest of the events are linked to timing. Every 10 seconds the EMIC is asked for a power measurement which is integrated over time to calculate the energy consumption. This power measurement is also compared to the previous measurement and if it is smaller the potential energy savings are also calculated. These two values are then stored and can be cleared by the user by setting the reset switch to "on" which will reset the values once. After 30 seconds have passed the voltage and current readings are requested from the EMIC and are sent to the platform with the energy consumption and potential energy saving values. The reason for the these two different timing intervals is due to the fact that power consumption in kWh needs to be calculated at short intervals by integrating the instantaneous power consumption over time, while it is not necessary to update the instantaneous voltage, current and power measurements so frequently

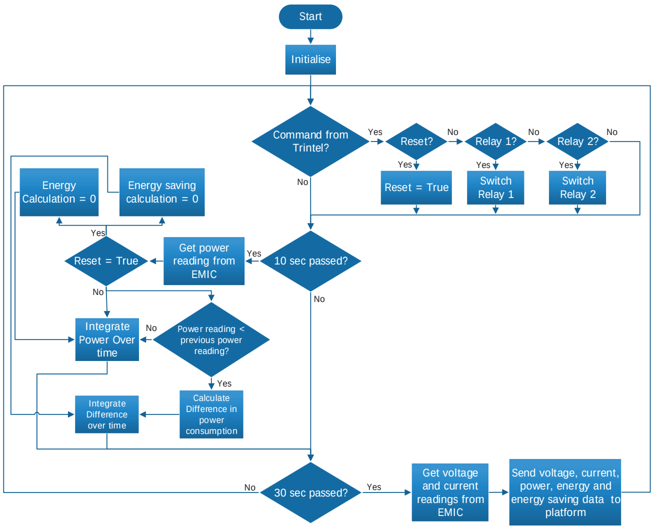

Fig. 5. Main Program Flow Diagram

A. *Smart Platform Communication*

The communication between the Beaglebone and the platform was performed using the BeagleBone's UART1.

Table 1 lists the different type of commands used in this project.

Table 1: AT commands used in this project

Command	Description
`at+cfun=1`	Restarts the modem
`at+boot?`	Reboots the modem
`at+cgsn`	Requests modem's serial nr
`at+awtda=c*`	Instructs modem to send all data back that it does not understand
`at+awtda=d*`	Instructs modem to send all commands back it does not understand
`at+awtda=d,”Home_control.Measure”,1,”V,INT32,230”`	This format is used to send the data variables to the SMART platform.
`at+awtda=a,”Home_Control”,1018977`	This format sends job acknowledgements to the platform.

In order to receive commands from the platform a function `uart1_read()` was written. When this function is called it reads and processes the command from the platform to determine what type of command it is. Once the command type has been determined the command is executed and an acknowledgement message containing the commands unique ID number is sent back to the platform.

The communication between the BeagleBone and the Platform consisted solely of data messages and the function `uart1_write()` was used to send this data. The `uart1_write()` function receives the data that has to be sent and converts it to a string format that the platform can interpret using a `String_Creator()` function.

B. *Power Sensor Communication*

The EMIC responds to host commands that are sent from the BeagleBone's UART2 port. There are four of these host commands needed to read and write data to and from the EMIC's registers as well as to give instructions to the calculation engine. The different types of commands are listed in Table 2**: Binary Structure for communicating with EMIC** found at [21].

Table 2: Binary Structure for communicating with EMIC

Function	Binary Value	Description
Register Read	00 A5 A4 A3 A2 A1 A0	A[5:0] specifies the register address
Register Write	01 A5 A4 A3 A2 A1 A0	
Page Select	10 P5 P4 P3 P2 P1 P0	P[5:0] specifies the page number
Instruction	11 C5 C4 C3 C2 C1 C0	C[5:0] specifies the instruction

To retrieve the power measurements from the EMIC two commands are sent to it using the `uart2_write()` function, namely Page Select and Register Read. These two commands tell the EMIC on what page and register the requested data is stored in respectively.

Once the EMIC has received a command to return a specific measurement it will send three bytes of register data to the BBB. This data is sent using a total of 10 bits per byte with one start bit, eight data bits, and one stop bit with the least significant bit first. The values that the EMIC sends to the BBB are in the range of -1 to 1 and this value has to be converted to the actual value by multiplying it with a factor that is determined during calibration. The function `uart2_read()` is used to read and convert the data to a most significant bit first format.

In order to calculate the energy consumption of the monitored device, the power measurement is retrieved every 10 seconds, as seen in Figure 5, and then integrated over time to get the energy consumption, E, in kWh. It is calculated using Equation 1.

$$E = \sum (P \times 10s \times \frac{1kW}{1000W} \times \frac{1h}{3600s}) \qquad (1)$$

This calculation is continually executed until the user triggers the reset command at the terminal which wil restart the process. The calculation process of the potential energy savings is started by comparing the current power measurement with the previous power measurement. If the current power measurement is at least 10% smaller than the previous measurement a counter is incremented. This process is repeated three times resulting in a delay of 30 seconds to make sure that a load has been switched off and that it wasn't just a dip in the power consumption. When the counter reaches three the difference in power consumption is calculated by intergrating over time using Equation 1. This intergration process will keep on executing until the current power consumption becomes more than the previous power consumption or until the user triggers the reset command.

VII. CONCLUSIONS AND RECOMMENDATIONS

The completion of this project was dependent on finishing two parts, namely the power measurement and platform communication systems. The power measurement circuit performed well as it communicated successfully with the Beaglebone and was able to measure the voltage, current and power to within an accuracy of 0.6%. This accuracy is attributed to the CS5490 IC that was used for the power measurements and was definitely a good choice for a project of this nature.

The communication with the Smart Platform was successful as data and commands could be sent to and from the platform enabling easy access to the power consumption measurements. The Trinity Smart Platform was perfectly suited to this project, it worked very well as it allows for complete customization, enabling a user interface to be created which is specific to this project. It proved to be an effective M2M platform.

The Beaglebone Black was chosen as the MEC and proved to be a very capable device and a lot was learnt from it. The ability to develop capes which can fit onto the Beaglebone's headers makes it a very customisable device. This also enables faster design and development of circuits that can interact with the Beaglebone and makes the possibilities of implementation endless.

One of the biggest problems found was the speed at which the power measurements could be sampled in order for energy usage to be calculated. With the EMIC's UART set to the default 600baud the updating time was limited. It is recommended that the baud rate be set higher so that the energy consumption can be calculated at closer intervals which would increase the accuracy of the calculation.

The calibration of the EMIC also proved to be a bit of a challenge as its accuracy can only be as good as the device used to calibrate it, as calibrating it with a normal multimeter was not sufficient. It is recommended to use a proper energy measurement device as this will significantly increase the ICs' accuracy.

To improve the effectiveness with which this system can help users save electricity a future iteration of this project should include not only the potential energy savings data but also the quantification of money that is being saved, thus re-emphasizing the incentive of reducing energy consumption.

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VIII. BIOGRAPHIES

Douw du Plessis received the BEng degree in Electrical and Electronic Engineering from Stellenbosch University in 2014.