Smart homes: A domestic demand response and demand side energy management system for future smart grids

Mohamed Sameer Hoosain and Babu Sena Paul

Abstract—Smart homes or the homes of the future will be equipped with advanced technologies for user comfort and entertainment. Intelligent systems will be available to ensure this comfort and reliability. With these technological advancements comes further energy management. The concept of domestic energy efficiency is a concern at present and will be, in the future. So how do we optimize homes and users as to how they conserve energy? Domestic user's energy usage represents a large amount of total electricity demand. Typical home energy systems utilize a rudimentary form of energy efficiency and management. In this paper we look at a Demand Response and Demand side management system model to curb this situation. The demand response system is achieved by the utility turning on/off smart power plugs wirelessly throughout the home based on peak and off peak periods via communication through its smart grid. To help consumers shift their loads during these times, appliance power sources that can act autonomously based on wired or wireless signals received from the utility via its smart grid is required. Users in response to this, connect their appliances to these plugs by generating their own hierarchy system by prioritizing their appliance usage. Whereas the demand side management system allows users to manually configure dates and times for the turning on/off of the smart power plugs wirelessly through the user's smart user interface. Therefore, an energy efficient future smart home that can save the user on monthly expenditure and save on energy simultaneously.

***Index Terms*—Demand side management (DSM), demand response (DR), energy efficiency, smart grid, smart homes.**

1 INTRODUCTION

Households in South Africa require an adequate amount of energy for domestic use such as cooking, heating, lighting and communicating. In order to improve living standards, health and reducing poverty it is of vital importance that the appropriate forms of energy are available. The unavailability of accessible/affordable modern energy, many households turn to numerous other sources such as wood, cow droppings and coal. Although these sources provide for practical energy usage it also exposes households to health hazards and contributes to environmental degradation. This type of energy usage is very common amongst the lower income households, and they often spend a higher percentage of their household resources and time. As compared to the higher income households to acquire enough energy to maintain even the simplest household activities [1]. To ensure more equitable access to electricity, that demand for electrical energy has increased and it is expected this will continue to increase significantly in the next five to ten years [2]. The graph in Fig. 1 depicts this increase in demand over the past few years [3].

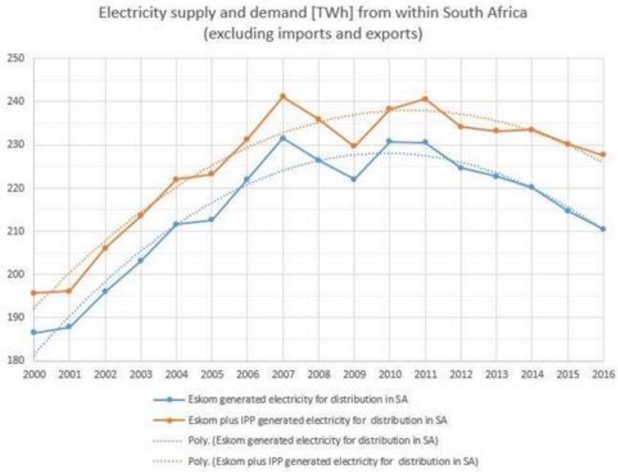

Fig. 1. Compares the supply and demand of electricity from within South Africa for the years 2000 to 2016.

According to results of census data from Stats SA, 89% of South African households use electricity for lighting, 77% of households use electricity for cooking, 66% of households use an electrical appliance such as the electric geyser (31%), an electric kettle and stove (7%) to heat water and 41% of households use electricity as the main source of energy for space heating and close to two fifths of homes use no energy source for space heating [3].

Despite the stated problems, according to The South African Social Attitudes Survey (SASAS) who has been monitoring consumer satisfaction in the country since 2003. Their results show that South African consumers are relatively satisfied with the provision of electricity by the Department of Energy. However, the latest residential energy survey by the Department of Energy South Africa show that on average, South African households spend 14% of their total monthly household income on energy needs which is higher than the international benchmark of 10% for energy poverty [4].

Therefore, this increase in demand for electricity means that the current electricity supply must be more efficiently utilized. A demand response and demand side management technique is proposed in this paper. We analyze the system models to determine whether the system provides optimum results in future smart grids to manage and minimize the

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daily electricity expenditure and improve the energy efficiency of future smart homes.

2 BACKGROUND AND DEFINITIONS

The discrepancy of the demand for electricity throughout the day has long been an issue for utility companies. During peak hours, pressure on utility companies increase significantly to provide consumers with sufficient electricity, and may even have to ration the electricity supply of certain areas when demand exceeds generation. Whereas, during off-peak hours, user demand is much less, therefore only small amounts of generators are needed, but there tends to be a waste in generation capacity due to the number of idle generators. [5]. Future Smart Grids have gained increasing attention as a means to efficiently manage the future smart homes energy consumption in order to reduce their peak energy usage, thus improving the performance of power generation and distribution systems [6]. A smart grid for smart homes is expected to be an innovation or modernization of the traditional electricity network. It provides supervision, protection and optimizing automatically and systematically to operation of the interconnected elements [7]. Demand response systems can be used to respond to grid condition and pricing signals encouraging consumers to utilize energy efficiently and reduce peak electricity demand through smart grid enabled energy management, therefore resulting in energy efficiency as well as financial savings for both, consumers and electric utilities [7]. In its 2011 annual report Eskom the national utility company in South Africa had mentioned that a demand response build-up pilot project had been launched which is expected to deliver 500 MW to the grid [8].

As electricity demand increases, public campaigns to promote energy cognizance increased. In a bid to reduce electricity usage, South Africa`s utility company Eskom embarked on campaigns to inculcate society about the consequentiality of preserving energy whenever possible. The latest campaign for energy-saving tips, dubbed the “49 Million Campaign”. It calls upon all 49 million South Africans to embrace energy-saving as a culture and to join the global movement towards ensuring a sustainable future. Another initiative is the National Power Alert Banner on television. It is a residential (DSM) system which allows households to take part in reducing the pressure on the national power grid by switching off unnecessary appliances. Other systems such as the smart pre-paid meters where users react to cost of consumption, but these also have their disadvantages such as; not all the information is presented to the user nor are they very user friendly. Targeting the demand side of the dilemma as a short-term response, whilst supply side amendments are simultaneously pursued on a more long-term substratum [2].

2.1 Current technologies

2.1.1 Demand side management

Any DSM technique implemented may result in one of the following forms of electricity demand reduction: Peak clipping, Conservation and Load shifting. In order to achieve this, technologies such as the following are utilized in current smart homes [15]:

1. Direct load control
2. Load limiters
3. Real time use of pricing
4. Smart energy meters
5. Smart appliances

Current research and work in this field is being done using DSM techniques with the use of smart energy meters and artificial intelligence, which can be found here [2].

2.1.2 Demand response and Smart grid

Whereas when looking at DR and Smart grid technologies in current smart homes, utilities consider DR as an undeniably profitable asset choice whose abilities and potential effects are extended by grid modernization endeavors. Current examples include; sensor networks that can see top load issues and use programmed changing to occupy or diminish control in key areas, removing the shot of over-burden and the subsequent power disappointment. Advanced smart metering framework grows the scope of time-based rate programs that can be offered to consumers. Smart consumer frameworks, for example, in-home displays or smart area networks can make it less demanding for consumers to change their conduct and decrease peak period utilization from data on their energy utilization and expenses [16]. Lastly artificial intelligent techniques such as Game theory and Neural networks are being used or further researched in DR and Smart grid programs for the current smart homes.

2.1.3 Arduino based models

Since the prototype used in this research consisted of the Arduino UNO microcontroller. We looked at how this piece of hardware has been used so far in Smart home applications. Research showed that home automation was a key application, other applications included temperature control, energy metering, remote management such as Wi-Fi or GSM and lastly smart phone control using custom applications.

The following definitions will be used in this paper and are often used in discussions on smart electricity management and usage:

2.2 Demand response

“Demand Response (DR) can be described as a term used for systems used to encourage electricity consumers to make short-term reductions in energy demand in response to a price signal from the utility companies. Typically, these reductions range between 1-4 hours which includes turning off or dimming of lights, or even shutting down a portion of a manufacturing process. [9].”

The ability of consumers to reduce electricity demand during peak periods through demand response activities is beneficial to the electric grid as a whole for two main reasons.

1. This can significantly reduce peak prices and overall price volatility for all users.

2. Demand response may reduce the need for further expensive infrastructure expansion for generation, transmission and distribution.

Historically, there has been some confusion when it comes to DR programs for electricity users. Broadly speaking it offers benefits to the electricity user and can be part of an effective energy management program. Yet it is designed to operate under different circumstances with different electricity reduction goals. DR has its respective advantages and limitations and if properly understood, this will allow for a more successful overall energy management program. [9].

2.3 Smart homes

"A home well enough prepared with distinctive structured wiring and circuitry to allow home owners to remotely control an assortment of automated home electronic devices [10]."

2.4 Smart grid

"The Smart Grid can be defined as an electric framework that utilises data, two-way, cyber-secure communication technologies, and computational intelligence in an incorporated manner over the whole spectrum range of the energy system from the generation to the end points of consumption of the electricity. [11]."

A few key requirements of the Smart Grid are listed below and are taken into account in this paper [11]:

- Renewable energy resources need to be taken into account in order to tackle the global climate change. (South Africa is ranked among the top twenty largest carbon emitters per capita because approximately 67% of its primary energy supply is derived from coal [12]. Therefore, the current energy increase and need for cleaner energy supply means current electricity supply must be more efficiently utilised);
- Energy efficiency can only occur with consumer participation such as Demand Response and Demand side management techniques;
- Secure communications between smart grid and smart homes;
- Improve management, energy storage, energy flow and lower cost of energy

2.5 Demand side management

"The orchestrating, implementation and monitoring of those utility activities designed to influence consumer utilization of electricity in ways that will engender desired vicissitudes in the time pattern and magnitude of a utility`s load. Utility programs that fall under the DSM category include: load management, new uses, strategic conservation, electrification, consumer generation and adjustments in market share [14]."

After the 1973 and 1979 energy crisis, the term demand side management was conceived. The electric power institute introduced demand side management publicly in the 1980s [14].

3 METHODOLOGY/SYSTEM MODELS

In this section, the theory, design and operation of the system prototype is investigated, implemented and discussed.

3.1 System model

With the help of smart grid technology for smart homes, traditional investments can be reduced by applying demand response systems. This is achieved by the utility turning on/off smart power plugs wirelessly throughout the home based on peak and off peak periods via communication through its smart grid. To help consumers shift their loads during peak and off peak periods, appliance power sources that can act autonomously based on wireless signals received from the utility are required. Users in response to this, connect their appliances to these plugs by generating their own hierarchy system by prioritizing their appliance usage. But consideration needed to be given to the practicality of the demand response idea, and the concerns that end-users could raise with having smart power plugs in their homes, such as optional disconnection in peak hours, thus a demand side management system is added. This allows the user to manually configure times and dates for the turning on/off of the wireless smart power plugs autonomously. Fig. 2 depicts the simple system model of the prototypes operation based on the explanation above.

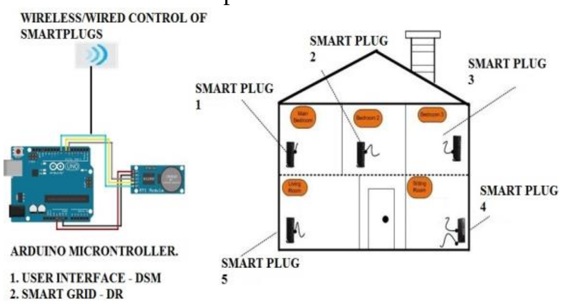

Fig. 2. System model.

3.2 Hardware and software

3.2.1 Main control unit/ User interface

The prototype allows for two modes i.e. the demand response mode where the main control unit communicates directly with the smart grid, and second mode allows the user to manually interact with device i.e. demand side management mode. This is done using an Arduino UNO development board. The Arduino is programmed using C-code on the Arduino Genuino software. Real time is applied to the system using a Real Time Clock (RTC). In order to keep the system up to date, a RTC with a backup battery is connected to the microcontroller, this allows for the real time and date to be saved at all times. The control unit/user interface is allowed to control up to seven wireless plug points via relays. The wireless technology used here was Radio frequency (RF). The relays would transmit a frequency when pulsed on or off by the microcontroller. To understand this further Fig. 3 depicts the circuit diagram of the Control unit/user interface.

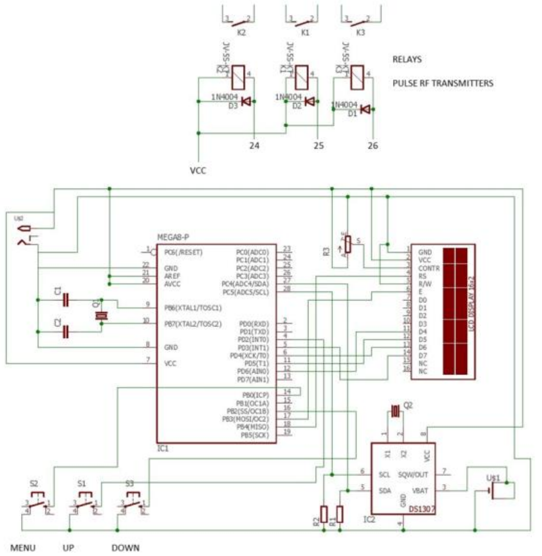

Fig. 3. Circuit diagram of the Control unit/user interface (transmitter).

For safety and completeness, the internal circuitry is housed inside a custom plastic casing. One input 230VAC cable is provided on the outside to power up the device and receive data from the utilities power communication lines (smart grid). Fig. 4 below depicts the completed control unit.

Fig. 4. Control unit/user interface prototype.

A user interface in the form of a 16 x 2 LCD with backlight and three push button switches (menu, up, down) are provided to the user. This allows the user to scroll through the menus. The menus displayed in Fig 5. allow the user to set the date and time which is saved on the RTC. It also allows the user to set the on/off times and days for each smart power plug separately.

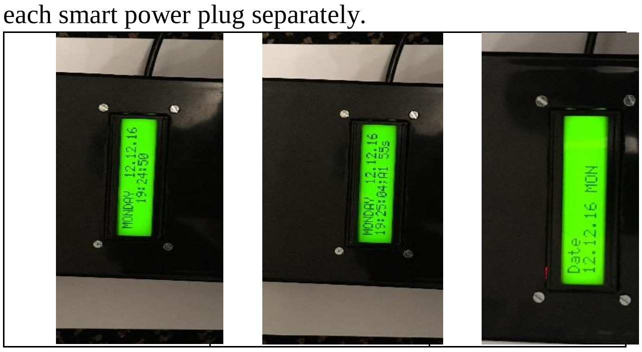

Fig. 5. Complete central control unit with user interface, and the different menus.

3.2.2 Wireless smart power plug

The wireless smart power plug is made up of a receiving unit specifically designed for a specific RF frequency. Each wireless smart power plug is unique in this regard. When the signal from the main control unit is received the wireless smart power plugs turn power on/off to the appliance/s connected to it. A 12VDC supply switches on a solid state relay which controls the turning on/off of appliances. The circuit output rating is 230VAC and up to 25A. Fig. 6 below shows the block diagram for the internal operation of the wireless smart plug.

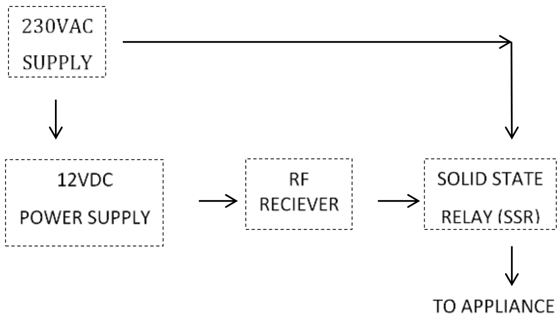

Fig. 6. Internal block diagram of the wireless smart plug (receiver).

For safety and completeness, the internal circuitry is housed inside a custom plastic casing. With the added indicator light which glows green when the specific wireless smart power plug has been triggered on. The smart power plug is simply installed directly to the homes supply line as would normally occur with any 3-pin plug point power supply in any home. The completed wireless smart plugs are shown in Fig. 5 below.

Fig. 5. Smart plug prototype.

3.3 Implementation

When the prototype is in the demand response mode The main control unit receives the updated and real time information from the smart grid. This information updates the lookup table pre-programmed within the microcontroller. Future smart grids will allow for communication to devices such as these in smart homes. Since this smart grid communication technology is not yet available to us, custom lookup tables had to be generated and be programmed within the microcontroller for simulation purposes.

The lookup table is made up of schedules based on time, date, peak/off peak costs and controlled on/off signals. Table I below shows an example of the look up table

Table I. Look up table example as at 2016/10/20.

Time	Peak Or Off Peak	Cost kwh (ZAR)	On/Off Schedule		
			PLUG1	PLUG2	PLUG3
19:56	Off Peak	0.94c	ON	ON	ON
19:57	Off Peak	0.94c	ON	ON	ON
19:58	Off Peak	0.94c	ON	ON	ON
19:59	Off Peak	0.94c	ON	ON	ON
20:00	Peak	R1.45	ON	OFF	OFF

Users connect their appliances to the smart power plugs by generating their own hierarchy system by prioritizing their appliance usage. This is done by connecting the appliances of highest priority to the 1st plug point and so on. Fig. 6 below describes a typical user appliance hierarchy.

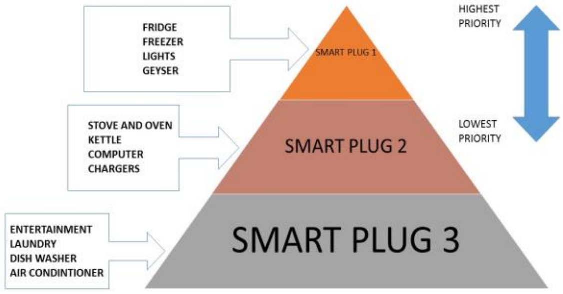

Fig. 6. Consumer based appliance hierarchy.

Similarly, the information in Table I (besides costs) can be configured manually by the user when the prototype is in the demand side management mode. The reason this option is designed is due to the fact that in our current time in our country some users might be disgruntled towards the utilities specified times to control appliances in their homes, as not all home owners operate under the same conditions.

The prototype was implemented for a total of ten single homes; data was recorded for each home. This data was then compiled within a spreadsheet and simulated graphically using Microsoft Excel. These results will be viewed and discussed in the Results section below.

4 SMART GRID COMMUNICATION

In the methodology section above it was mentioned that the main control unit receives the updated and real time information from the smart grid. This information updates the lookup table pre-programmed within the microcontroller. Future smart grids will allow for communication to devices such as these and future smart appliances in smart homes. Since this technology is not available to us at present, in this section we look at the possibilities for this future enhancement, and how can it work with the current prototype.

Smart grid communication technologies differ but are supported by two main techniques, which we know as wireless and wired. This can be used for communication between the utility using its smart grid and the technology in the future smart home. In this prototype we have sampled both techniques i.e. Wireless (frequency) and wired (networking). But they do have their advantages and disadvantages, for instance: wireless is more low cost and easier to use as compared to wired. However, the wired solution does not have signal interference nor does it need backup energy support.

Basically, a smart grid system can be broken down into two types of information infrastructure for information flow.

1. From sensor and electrical appliances to control units or smart meters;

2. Between the control unit or smart meters and the utility.

The first flow is described in the paragraph above. There are already available technologies such as power line communication or ZigBee for this section. Whereas the second flow, technologies such as cellular networks or the internet can be used. Cellular networks can fit the bill for communicating between the control unit or smart meter and the utility. Since this communication platform already exists therefore operational cost and infrastructure delays will be reduced. Cellular network will allow for a wide area environment. The same can be said about a wired internet connection, as telephone and ADSL lines as well as newer and faster lines are already being installed, the advantages would be the same as cellular networks. The only concern is cyber security and extra measures would need to be taken for the future smart home [13].

5 RESULTS

In this section, we present simulated results specifically for the demand response mode, and assess the performance of our proposed system for future smart grids and an energy efficient future smart home that can save the user on monthly expenditure and save on energy simultaneously.

We begin by assessing the load that the grid has to deal with during a 24-hour period for a specific area, in this case a group of 10 homes. This is then compared to the results, if an energy efficient system is utilised, and how does this reduce the load on the grid. In this case a Demand Response system is reducing electricity usage during peak hours and high prices. During the peak hours of 11, 14 and 17 energy prices spiked and the utility reduced its demand by turning off specific smart power plugs during these hours. Fig. 7 below describes the above results graphically [9].

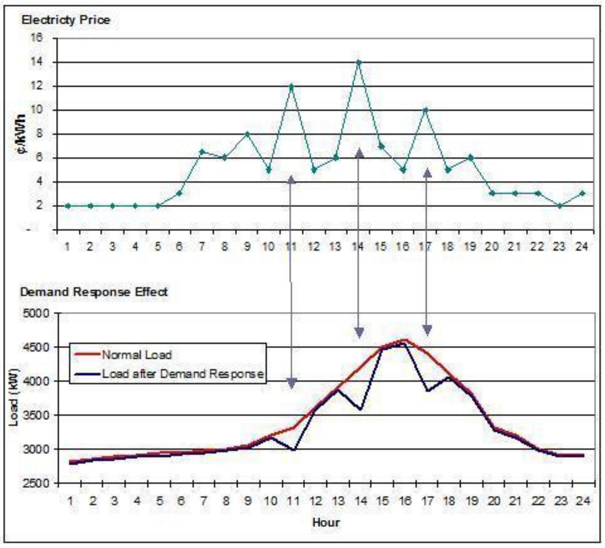

Fig. 7. System results.

To understand the system results in more detail, electricity usage was measured over a one-month period for a single home. Table II shows the data that was recorded for each appliance.

Table II. Monthly usage and cost for the most common appliance usage for a single home.

Appliance	Average watts	Monthly		
		Hours used	Approx. kwh	Cost 94c/kwh
Radio	70	100	7	6.58
Stove	400	3	1	1.128
Television	200	180	36	33.84
Lights	26	300	8	7.332
Heater	1500	180	270	253.8
Charging	75	13	1	0.91
Total				303.59

The electricity cost was set at 94c/kwh. It was found that the heater had consumed the most of the power in the home. Of course this would change during the summer months. Due to this type of usage the total monthly expenditure to the user was R303.59.

In order to reduce the energy usage and expenditure with the use of the prototype, the usage times of three non-essential appliances were reduced by half (i.e. television, radio and charging). By doing this the monthly expenditure was reduced by approximately 10% [2].

6 FUTURE WORK

Future work would include determining specific appliance load profiles rather than that of a single home, this would assist in future demand response management techniques. Home owners do not understand the physics behind energy usage but neither are the experts in the field as they do not possess the usage patterns. Other work includes introducing systems such as the one in this paper into the commercial and industrial sectors, and not just for domestic use.

7 CONCLUSION

By implementing new intelligent methods of producing, distributing and managing electricity in an efficient manner, we have reached a new way of thinking in this era. In this paper, we had investigated the effect of a demand response system and a demand side management system in a smart home with future communications technologies for smart grids. It was found that with the use of the prototype it is possible not only to save on energy but reduce the consumer's monthly expenditure. Clearly, there are many more open research issues in this area of research.

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