Transformation of Conventional Houses to Smart Homes by Adopting Demand Response Program in Smart Grid

Mohammad Shakeri and Nowshad Amin

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Abstract

In an ever-growing state of electricity demand due to population growth as well as modernization of societies, it has compelled us to look for many options to cope with the situations. However, for a balanced electrical power demand and supply, it is necessary to respond requirement at any time without any interruption with the strategy of demand response programs (DRP) to the users. In order to promote smart usage of electrical power, smart grid networks are gradually transforming conventional grids in many places. As a part of smart grid, conventional houses may be transformed to smart house by simply implementing some intelligent controller with interfaces like smart plugs to the conventional electrical appliances. This chapter elaborates a new strategy of home energy management system (HEMS) in a smart grid environment to transform any ordinary premises to smart house to be energy efficient by simply rescheduling operation time.

Keywords: smart grid, demand response, home energy management systems (HEMS), smart appliance, smart plugs

1. Introduction

Until recent times, peak-hour electrical demand and supply were usually controlled by human-interface-based load control approach. The strategy required cooperation of the consumers to calculate and analyze their consumption in peak hours to reduce their consumption and eventually electricity costs. Although this strategy was simpler and cheaper for utility companies, the method was not effective in most of the cases as usually consumers lacked knowledge about the consumption of their electrical appliances. Therefore, changing the perspective to smart usage of electrical power within the limitation, a new avenue called demand response programs (hereafter, DRPs) is considered as the most helpful to control the electricity consumption [1]. This may be realized by simply replacing the conventional electrical appliances to smarter appliances or even installing some smart interfaces like smart plugs to convert them to smarter ones.

DRPs enable us to reduce the greenhouse gas emission and improve grid efficiency as well as stability of the power plant by the smart usage of the electricity. In other words, more efficiency in the electricity market can be achieved by smartening the supply, consumption, distribution, and storage methods. Some of the advantages of using DRPs are listed as follows:

- The programs can reduce the overall power consumption at peak hours and consequently reduce the electricity price by shifting the loads to off-pick hours.
- The programs can help the utility companies to economically produce electricity.
- The programs can be useful in abnormal or emergency conditions.

According to some studies [2, 3], DRPs are defined as the modification in demand by shifting or shedding the loads when there is a shortage or excess of power in response to the condition of suppliers. Since 1970s, DRPs appeared in the United States to control peak hours. In those decades, incentive programs [4] and priced-based programs such as time of use price (TOU) [5] were utilized to analyze and control the demand [6]. In the following decades, gradually other strategies and techniques have been used as demand response programs such as critical pick price (CPP) [7], real time price [8], 1-day-ahead price [9], and incremental block rate (IBR) price [10, 11]. **Figure 1** shows the different types of demand response programs used till date in a chart.

However, DRPs could not individually reduce the electricity consumption or increase the rate of participants, as consumers do not have enough knowledge or cannot calculate and analyze their power consumption to control the electrical appliances according to commands from the utility companies [12]. Thus, intelligent equipment and technologies in grid infrastructure have appeared to control the dwellings’ electricity consumption independently.

Nowadays, it is possible to develop small, cheap, and efficient smart controllers that can be used to gather different types of data, store, and analyze them by utilizing integrated technologies such as embedded systems, microcontrollers, and wireless communication technologies. Network sensors have a wide range of application in many aspects such as smart homes, military services, forecasting, industrial agriculture, and building energy management system.

Collected data can be sent in any communication ways, such as wireless network or to the host services to be shown on the web [13] in real time. Intelligent buildings are new concepts that refer to an electricity demand that use sophisticated technologies to provide better performance for energy management system. This could happen by using smart controllers besides the bidirection communication that enables the utility companies to monitor and control the power consumption of the group of residential units autonomously [14, 15].

Energy management systems can control the operation of appliances in response to electricity price or commands of utility companies to optimize the electricity consumption at peak hours. This can be done by smartening the electrical appliances in residential units to control their

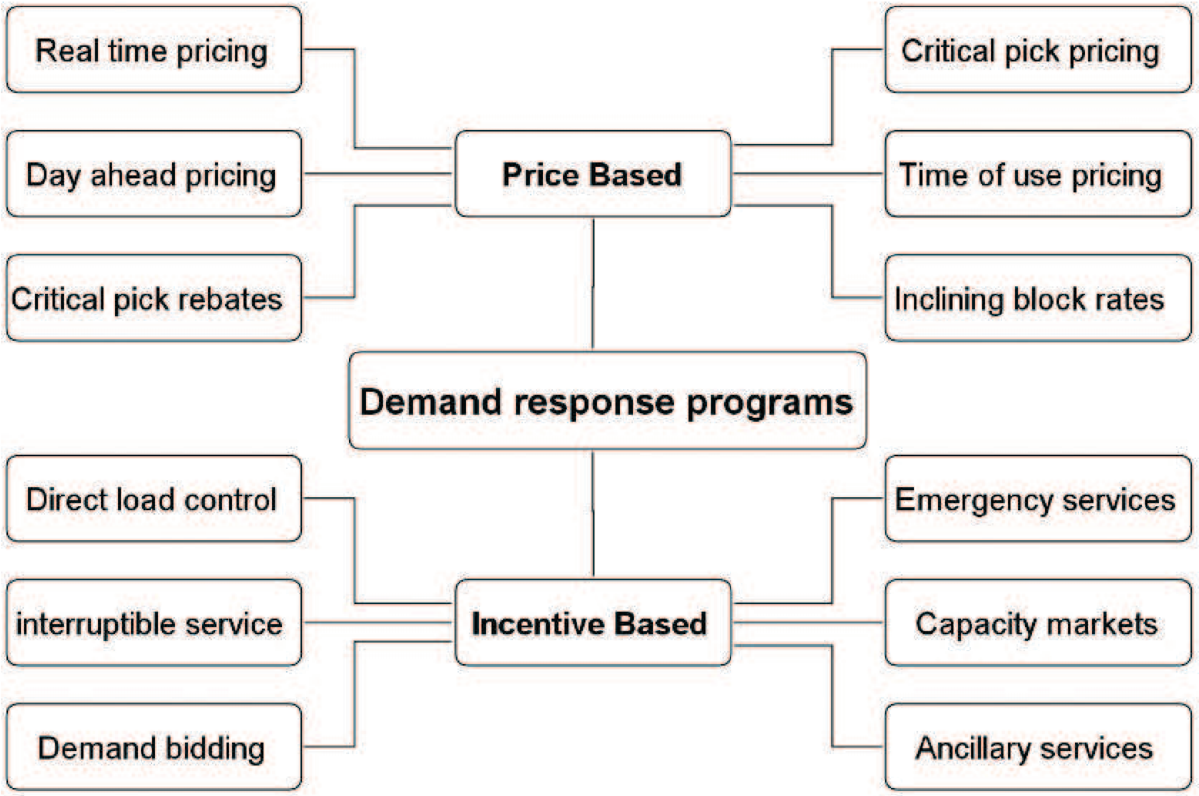

Figure 1. Demand response programs used till date.

power consumption. However, the majority of appliances that are used in demand are still uncontrollable and they cannot participate in demand response programs to optimize the overall power consumption. Therefore, the main objective in participating in smart grid is by converting the conventional electrical appliances into the smart appliances by utilizing smart plugs. These smart plugs are able to monitor and control the electrical appliances by running on scheduled operation of the appliances.

2. Development of electrical grids

2.1. Conventional grid

Over the last few decades, government bodies in many countries were responsible for controlling and monitoring of the electrical power plants while power systems were barely owned by the private sectors. The grid was designed to look like a tree, where generators were considered as the trunks, transmission paths represented as the branches, and loads considered as leaves [16] as shown in **Figure 2**. Therefore, this structure of the power plants was not efficient enough to ensure the benefits of the producers.

Privatization of the power system was the key solution for many governments to provide the competitive market at different levels of generation, distribution, and transmission. Therefore,

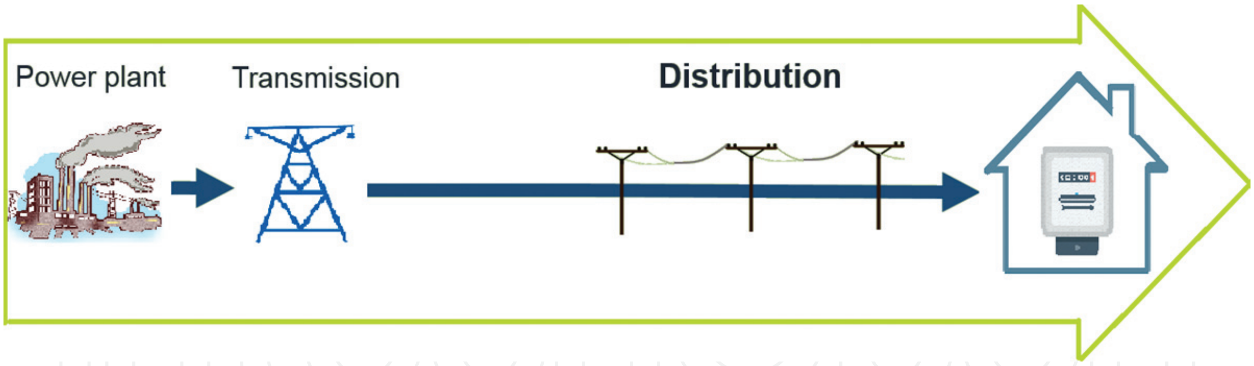

Figure 2. Structure of the traditional power plants.

electrical power industry was split into two categories such as the wholesale sector to be managed and controlled by government and the retailer sector to be controlled by private companies.

Until recently, the wholesale sector consisted of the generation side that produces electric power in bulk volume and transmits it to the demand sites and industries through transmission lines. Then, the retailer companies purchased the electricity on behalf of demand side. Therefore, in this deregulated electricity market, only the generation side competed with each other to sell their product to customers in order to increase their profit, while demand side had no power/activity in this respect.

In other words, demand side dealt with electrical power like a merchandise that was always available. Therefore, this issue showed the kind of rigidity of the power plants. Sooner, it was realized that demand side needed to participate in the energy market as a tool to control the power consumption and would yield any cost to be purchased for electrical power. The outage is the most important uncertainty in generation side, which may have occurred by the lack of generation or excess of demand. Moreover, the current grid is not built and designed for variable renewable energy generation and interactive demand response programs. Hence, the grid of the future should accommodate the changes [17].

2.2. Smart grid

The spread of renewable energy resources, demand response programs, and distributed generators put the traditional grids, which are commonly designed based on the centralized and fuel-based generators, to face challenges such as increasing the efficiency of the grid and reducing the greenhouse gas emission [6]. Furthermore, there are many important factors such as the consumer's participation in the electricity market, integrating the new technologies, and improving the reliability of the grid that have led to incorporate the smart grids in many countries.

The smart grid is the new conception of bidirectional flow of data as well as the electricity power. This can lead to the higher flexibility of the grid to be monitored, controlled, and communicate between the supply chain and demand side to improve the efficiency, reduce the consumption and electricity price, and thus maximize the reliability of the electricity supply chain. Continual development of electrical energy technologies such as distributed generators, storage devices, and demand management systems has been changing the ways of production and consumption of the societies. These methods enable us to reduce the greenhouse emission and improve the grid efficiency and stability. Moreover, we can achieve more efficiency in electricity supply chain by providing a smart supply of the energy as well as smarter consumption.

Nowadays, a large number of renewable generators with the lower power production have joined the grid tree. The utmost problem of renewable energies is that their flexibility is lower than the fuel-based generators, in other words, the output power of renewable energies is uncontrollable and depends on the atmospheric conditions. Smartening the grid and transforming the consumers from static users to the active players are the key issues to overcome the lack of flexibility. In order to achieve this, some rules are made and operated through utility companies that are called demand response programs. The main goal of using DRP is to shift or shed the loads from peak to off-peak hours to shave the overconsumption at peak hours.

Utility companies are able to operate the DRPs through home energy management systems (HEMSs) over the smart grid infrastructure. HEMS is an important part of the smart grid that enables the residential customers to execute demand response programs autonomously. There are many autonomous control systems to help the utility companies to reduce the overconsumption at peak hours efficiently; however, it may limit or violate the residents' comfort in many cases.

The main objective of HEMS is to optimize the electricity consumption during peak hours and consequently optimize the electricity price at the minimum sacrifice in the residents' comfort. Smart electricity dispatching among users and an optimal electricity consumption pattern would be beneficial from HEMS. Energy pricing, CO_2 management, electricity consumption monitoring, and demand consumption detection are only some of the applications of house automation as HEMS.

The presence of distributed generation such as solar, wind, biomass, and storage devices will help to efficiently save the peak hours without sacrificing the resident's comfort by using HEMS. **Figure 3** represents the infrastructure of the smart grid with HEMS.

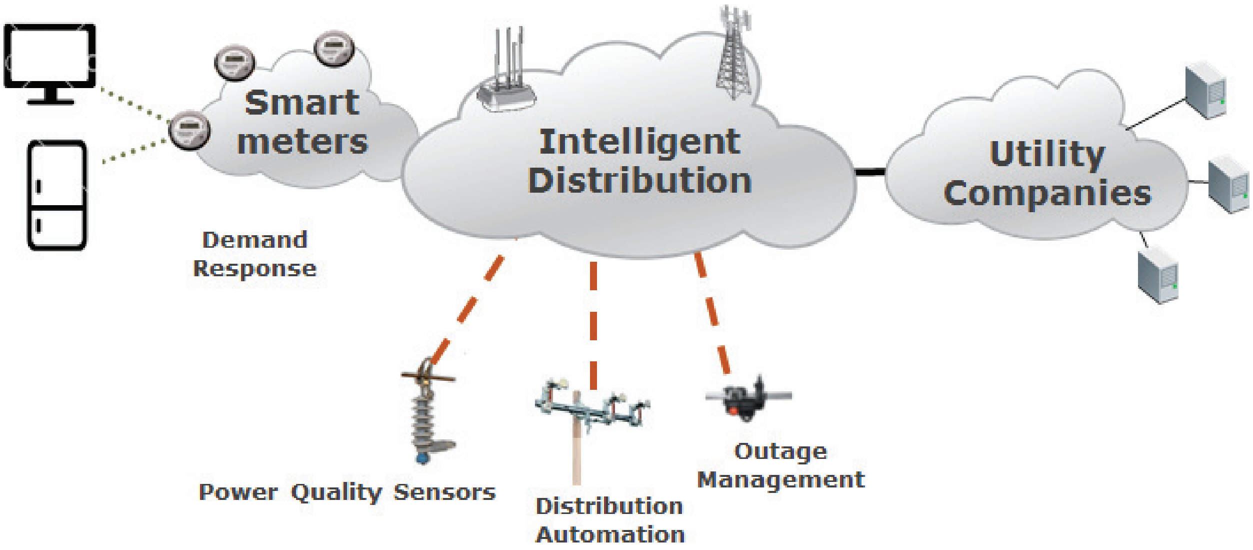

Figure 3. Infrastructure of the smart grid with HEMS.

HEMS consists of smart meter and smart appliances. Smart meters are devices to collect, monitor, and analyze the electricity consumption of the demand. These data are sent to the utility companies in real time to ensure more accurate electricity bills. Such devices provide many services such as electricity quality monitoring (voltage and frequency), demand control, dynamic service tariffs, and so on. In the smart home, electrical appliances are networked together and allow users to access and operate the appliances through a local controller or the Internet. Smart appliances are also able to respond to signals that are sent by utility companies to optimize the electricity usage during peak hours.

3. Proposed home energy management system

As mentioned earlier, HEMS is a demand response tool that helps utility companies to shift or interrupt the demand to optimize the power consumption and production. HEMS has the ability to make a communication between smart appliances and utility companies to improve the energy consumption of the premise. HEMS is utilizing the smart appliances and smart meter (local controller) to monitor and control the overall power consumption of the residential dwellings. Smart appliances are able to communicate with the smart meter, which is responsible for collecting the required data of the smart appliances for further analysis. **Figure 4** shows a simple structure of the smart home. Currently, the majority of the appliances in residential units are traditional and uncontrollable. Therefore, it is desired to convert the traditional electrical appliances to the smart appliances through smart plugs and smart meter. This is more complicated than a simple on and off switch. For instance, a smart air conditioner might extend its cycle time slightly to reduce its consumption on the grid.

In the following sections, smart meter, as well as smart plugs and transmission unit, will be introduced briefly.

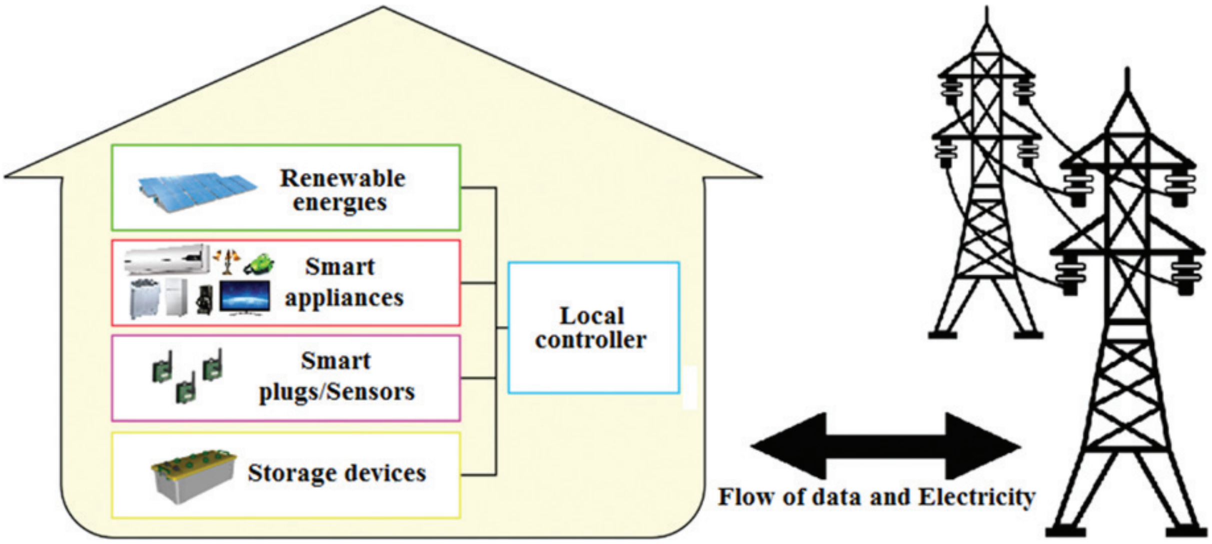

Figure 4. Simple structure of smart home (HEMS).

3.1. Smart meter/controller

Smart meters are devices to collect, monitor, and analyze the electricity consumption of the demand. These data are sent to the utility companies in real time to ensure more accurate electricity supplies. Such devices provide many services such as electrical power quality monitoring (voltage and frequency), demand control, dynamic service tariffs, and so on.

Integrating smart meters to premises involves complex communication technologies and may lead to relevant economics and environmental profits for power companies and consumers. As an example in demand side, consumers can be informed remotely on energy costs and related carbon emission data. These data can be recorded and displayed online for the consumers.

A smart meter consists of two main parts such as local controller and transmission unit. At each time interval, smart meter aggregates the data from smart plugs, analyzes the data, and communicates with utility companies for further decisions. The smart meter aims to control the operation of appliances on the grid to decrease the electricity cost taking price signal and occupant's comfort into account. **Figure 5** represents the simple structure of the smart meter. Eq. (1) demonstrates the cost of electricity function, while C_P is the cost of electricity at the time τ, and T_G indicates the consumed power from the grid at the time τ

$$\text{Electricityprice} = \sum_{\tau=1}^{24} C_P(\tau) * T_G(\tau) \tag{1}$$

3.2. Smart plugs for conventional electrical appliances

The smart plug consists of three main parts such as a sensing unit, a micro-controller unit (MCU), and a transmission unit as shown in **Figure 6**. The aim of using the smart plug is to convert the conventional appliances to smart appliances.

A. Sensing unit: This unit can collect the ambient data, convert the analog data to digital, and send them to MCU unit. Current, voltage, temperature, and light lumens are some of the parameters that could be measured through sensors. These data are aggregated through MCU and sent to the local smart meter via wireless communication for further analysis. As an example, ACS 712 current sensors with Hall Effect measurement besides the lm 35 temperature sensors are used here as an example.

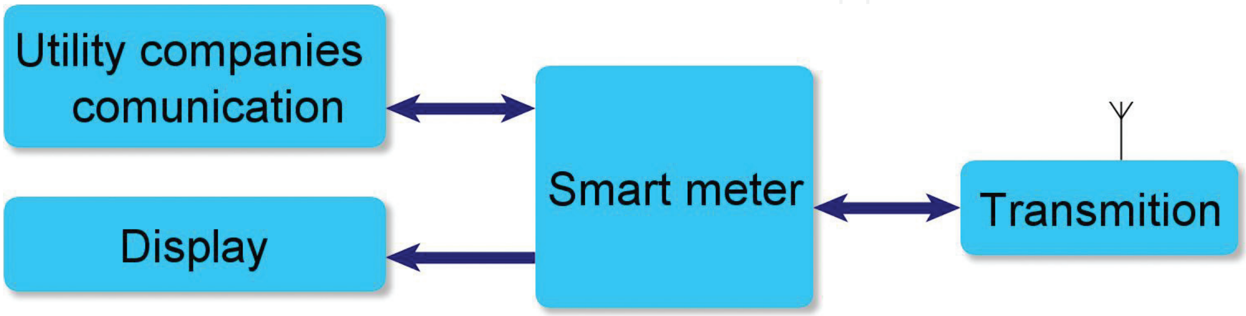

Figure 5. Simple structure of a smart meter.

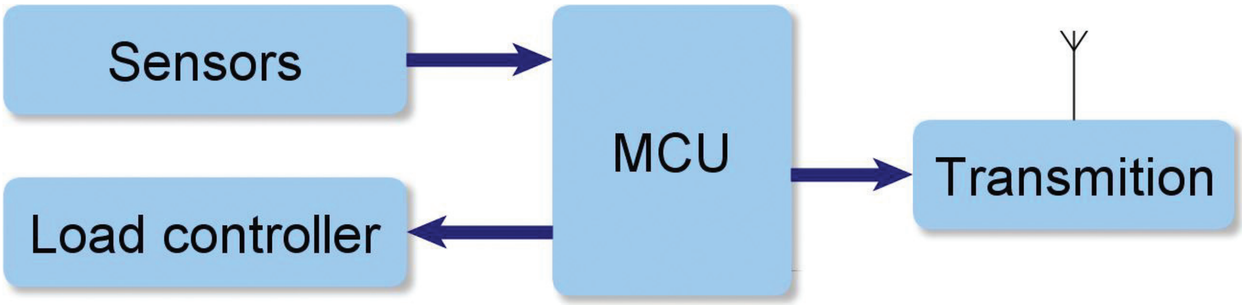

Figure 6. Simple structure of an intelligent wireless smart plug.

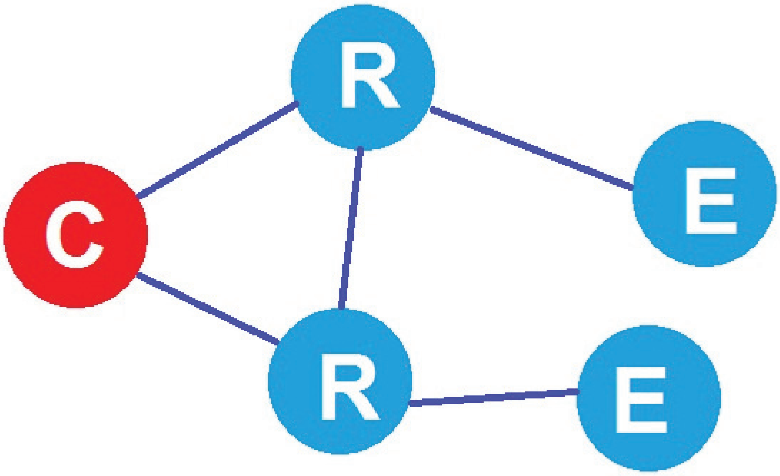

Figure 7. Layout of the communication among wireless modules.

B. MCU unit: This is the central unit or the microcontroller unit, which is interfaced to the sensor units and responsible for analyzing, storing, and sending the collected data to the local controller/smart meter through the transmission unit.

C. Transmission unit: This unit is responsible for sending the collected data by MCU as well as to the smart meter [18]. XBee 802.15.4 model XBIB-R-DEV enables us to send data via wireless communication with low power consumption and low cost. The operating frequency of this module is 2.4 GHz. It has serial USART interface connection, which makes it easier to interface with other devices. **Figure 7** represents the layout of the communication among smart plugs, whereby C is for coordinator, R represents router, and E represents end user.

The smart meter is connected to a coordinator wireless module and smart plugs are connected to the routers/end users. When a new device is connected to the network, it sends a predefended frame, which includes the type of module that could be a router or an end user and address of the module. The smart meter reads the data then about the module and stores the 64-bit address of the module in its EEPROM. Therefore, from then onwards, the smart meter can communicate with the smart plugs through the wireless network of XBee modules. **Figure 5** shows the implemented smart meter as well as the smart plug.

Smart plugs that are proposed and implemented in the HEMS are categorized in two groups. The first category is the normal smart plugs. These plugs can control the electrical appliances by measuring the power consumption of them and send/receive the commands to/from a smart controller. The second category of the smart plugs is the thermal smart plugs. These plugs are connected to the thermal appliances such as air-conditioning system and refrigerator. They are able to measure the inside temperature of the thermal appliances beyond the ability of normal smart plugs.

3.3. Energy management strategy

There are many methods to reduce the power consumption during peak hours such as direct load control [19], dynamic electricity pricing to incentivize the costumers [20], load management based on game theory [21], and keeping the overall consumption of the building under the certain value [22], which are used as the optimization strategy for electricity price minimizing in this chapter. In order to reduce the electricity price according to Eq. (1), it is required to reduce the electricity consumption ($T_G(\tau)$) as much as possible. Therefore, the smart meter tries to keep the overall consumption of the building under the predefined value. Residents can turn on any appliance at any time. Each smart plug is interfaced with one appliance; therefore, when one of the residents tries to turn on an electrical appliance, the related smart plug sends a request to the smart meter. Then, the smart meter checks the electricity price, rated power, as well as the priority of the related appliance. If the electricity price is cheaper, related electrical appliance will be operating on the grid. Otherwise, the operation of the electrical appliance with the lower priority value is curtailed for some time, and a new appliance operates on the grid. However, if the priority of the new appliance is lower than the other appliances, the operation of the new appliance is delayed for some time to keep the overall consumption of the building under that predefined level.

4. Observation and analysis of the proposed HEMS

The aim of using the smart controller is to manage the appliances on the grid to optimize the electricity price. A case study has been observed in a studio-type apartment with ordinary electrical appliances for two persons as shown in **Table 1**. The priority of the appliances is adjusted by residents based on their comfort level. Here, it is assumed that the utility company sends signal to the smart meter to keep the overall consumption of the building ($T_G(\tau)$) under the 3000 W at any time interval. Otherwise, the electricity price will be increased as the penalty for the residents.

The apartment is then equipped with the proposed intelligent plugs to control the electricity consumption during daytime. In order to understand the performance of the intelligent plugs and smart meter, two scenarios are studied and compared, which will be discussed in this Section. It is assumed that electricity price is calculated and sent by the utility company at each time interval. As an example, **Table 2** shows the hourly changes of electricity price during 24-h

Electrical appliances	Rated power (W)	Quantity	Priority
Refrigerator	200	1	7
Air conditioner	1600	1	9
Coffee maker	1200	1	6
Toaster	1000	1	5
Iron	1000	1	8
Television	100	1	8
Fan	70	1	7
Hair dryer	1300	1	6
Lamps	90–110	4	8
Low wattage devices	80–110	2	7

Table 1. Rated power and priority of electrical appliances.

Time (h)	Electricity price ($)
00:01–05:00 AM	0.05
05:01–09:00 AM	0.12
09:01 AM to 03:00 PM	0.09
03:01–07:00 PM	0.12
07:01–09:00 PM	0.09
09:01–00:00 PM	0.05

Table 2. An example of electricity price during 24-h interval [23].

interval. The aim of the HEMS is to keep the overall consumption of the apartment under the predefined level.

Now, in order to understand the performance of the smart plugs, two different scenarios are opted. In the first scenario, residences are using electricity from the grid without any control algorithm and they are prioritizing their comfort at any cost. Therefore, the temperature of the apartment is set at 18°C, while the output temperature is varied between 24 and 30°C. The power consumption of the appliances without optimization algorithm from 5:00 to 22:00 h is shown in **Figure 8**, at the time the electricity price is more expensive.

As found in **Figure 8A**, there are some overconsumption times during 6:00 and 8:00 as well as 12:00 and 14:00 h. The room temperature is fluctuating around 18°C. Electricity consumption of the house without any control on the operation of the appliances during 24 h is 21 kWh and the total price is 2.04 USD/day.

By contrast, the overall power consumption of electrical appliances with optimization algorithm as scenario 2 is shown in **Figure 9** at the time when the electricity price is more expensive.

Results show that the total consumption of the building is 20 kWh by deploying the intelligent plugs during 24 h and the total price during 24 h is 1.85 USD/day. **Figure 8A** shows the

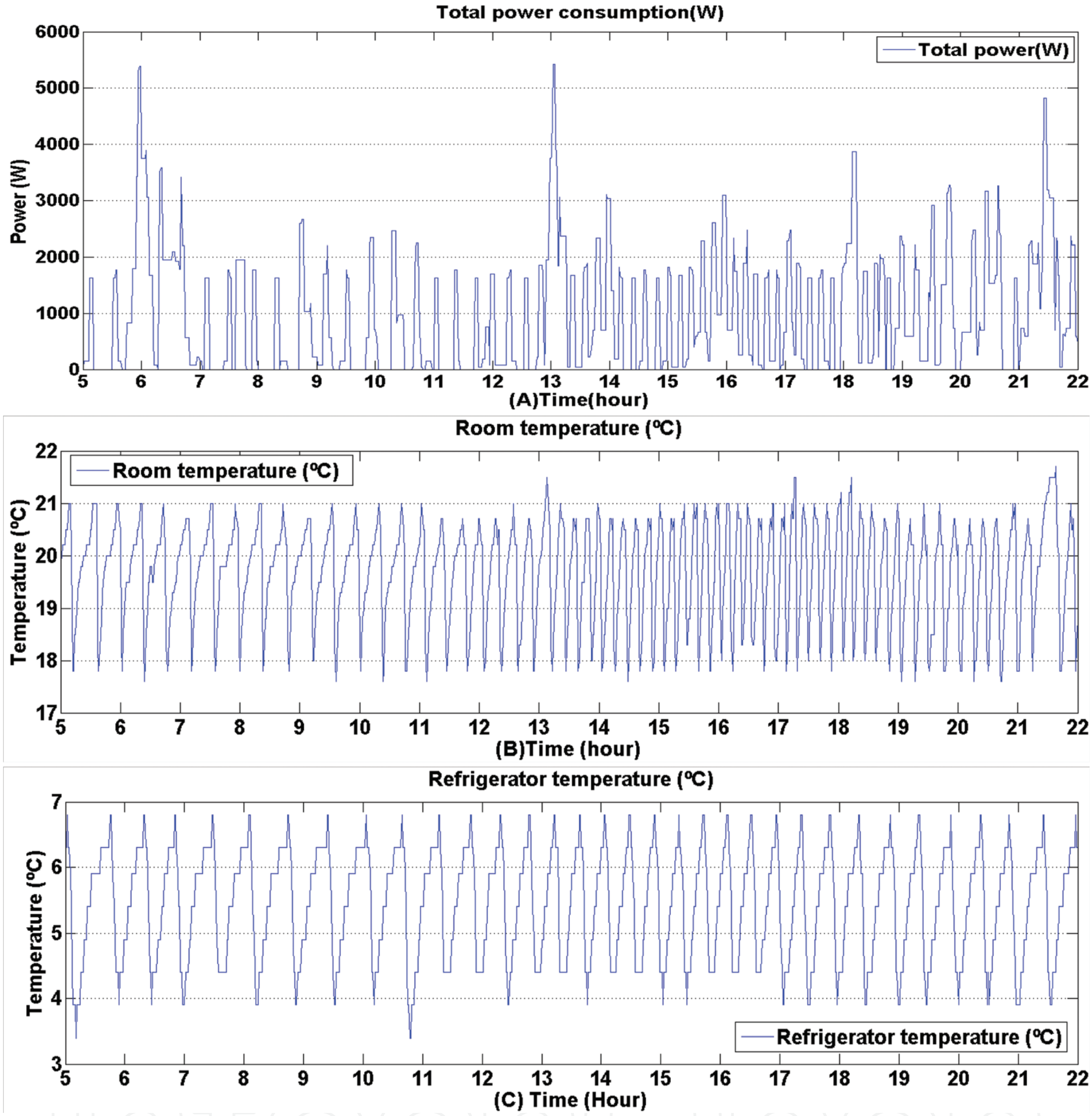

Figure 8. (A) Total power of electrical appliances without using smart plugs and controller, (B) Room temperature fluctuation during the period and (C) Refrigerator temperature.

success in controlling the temperature of the building as well as shifting the operation of the shiftable appliances during peak hours. As an example, the overconsumptions between 6:00 and 8:00 h as well as 12:00 and 16:00 h are decreased after the deployment of the smart plugs and smart controller.

Table 3 shows the comparison between two scenarios executed in terms of the total power consumption of the electrical appliances in a day.

As found here, deployment of the proposed smart plugs can reduce the electricity price by approximately 8% as demonstrated in scenario 2 as compared with the home without any

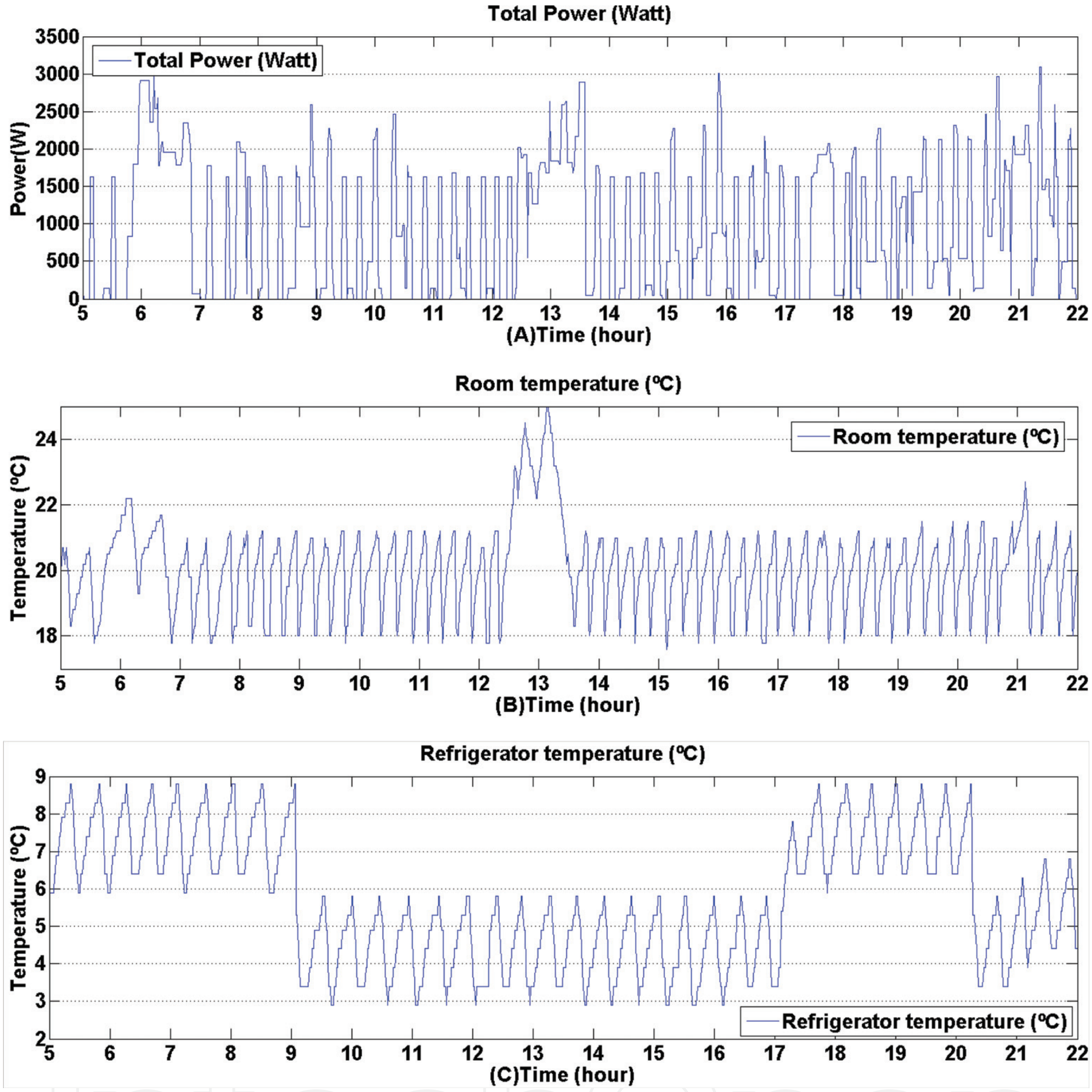

Figure 9. (A) Total power consumption trend of electrical appliances after deploying smart plugs, (B) room temperature fluctuation, and (C) refrigerator temperature fluctuation during the period.

Case studies/scenarios	Total consumption (kWh)
Without optimization strategy and smart plugs	21
Utilizing the optimization strategy through smart plugs	20.40

Table 3. Comparison among the scenarios.

control as shown in **Figure 10**. This saving comes from deferring the operation of the shiftable appliances as well as from controlling the temperature of the house. Comparing between the usual case and HEMS-adopted scenarios, it is obvious that the utilization of smart plugs in

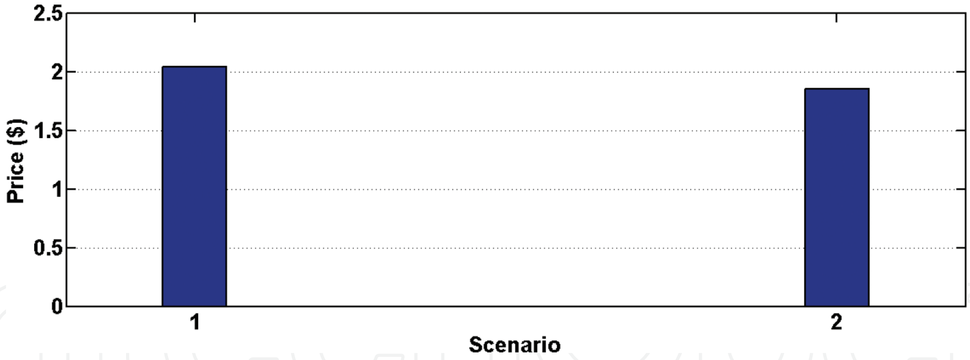

Figure 10. Comparison of the purchased electricity price between two different scenarios.

dwellings has a huge impact on the overall power consumption and consequently it cuts off the electricity price. Therefore, it is obvious that smart plugs and smart controller as HEMS play an important role in the future of the DRPs.

5. Conclusion

In this chapter, home energy management system (HEMS) as a part of smart grid is introduced, where smart plugs along with a controller are designed to optimize the overall power consumption of any ordinary house. These plugs can control the overall power consumption of the appliances, aligning with the electricity price in places where electricity price is calculated by utility companies in advance and sent a day ahead or in real time to the smart meter. The smart meter then controls the electrical appliances through smart plugs according to the priority of the appliances, electricity cost, and rated power of appliances to optimize the electricity consumption in case of certain limitations. The results show that the proposed wireless smart plugs together with the controller are able to reduce the electricity cost up to 8% per day by shifting the operation of the electrical appliances to optimized time slots. Hence, the implemented algorithm through smart controller and smart plugs has the potential to minimize the electricity price by simply optimizing the power consumption during peak hours on a distribution grid to be recognized as a part of smart grid.

Author details

Mohammad Shakeri[1] and Nowshad Amin[1,2]*

*Address all correspondence to: nowshad@uniten.edu.my

1 Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia

2 Institute of Sustainable Energy, Universiti Tenaga Nasional, Jalan Ikram-Uniten, Kajang, Selangor, Malaysia

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