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Real time optimal schedule controller for home energy management system using new binary backtracking search algorithm

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ABSTRACT

In the domestic sector, increased energy consumption of home appliances has become a growing issue. Thus, reducing and scheduling energy usage is the key for any home energy management system (HEMS). To better match demand and supply, many utilities offer residential demand response program to change the pattern of power consumption of a residential customer by curtailing or shifting their energy use during the peak time period. In the present study, real time optimal schedule controller for HEMS is proposed using a new binary backtracking search algorithm (BBSA) to manage the energy consumption. The BBSA gives optimal schedule for home devices in order to limit the demand of total load and schedule the operation of home appliances at specific times during the day. Hardware prototype of smart sockets and graphical user interface software were designed to demonstrate the proposed HEMS and to provide the interface between loads and scheduler, respectively. A set of the most common home appliances, namely, air conditioner, water heater, refrigerator, and washing machine has been considered to be controlled. The proposed scheduling algorithm is applied under two cases in which the first case considers operation at weekday from 4 to 11 pm and the second case considers weekend at different time of the day. Experimental results of the proposed BBSA schedule controller are compared with the binary particle swarm optimization (BPSO) schedule controller to verify the accuracy of the developed controller in the HEMS. The BBSA schedule controller provides better results compared to that of the BPSO schedule controller in reducing the energy consumption and the total electricity bill and save the energy at peak hours of certain loads.

1. Introduction

Many critical shutdowns happened in the electric power networks in many countries such as in Italy in 2003, Indonesia in 2005 and in both Canada and United States in 2003 [1]. Power outages sometimes occur due to increased number of residential appliances, increasing cooling and lighting demand and over-demand from customers in the period of peak hours [2]. Peak time load occurs in the grid when most customers are using electricity at the same time in a day [3]. As a solution to meet the high power demand, electricity suppliers are forced to increase generation by building additional conventional power plants [4]. However, this solution is unsustainable because of low plant utilization factor, increased carbon dioxide emission that contributes to climate change and increased the costs of investment [5].

Demand response (DR) program is one of the demand side management (DSM) solutions that has been investigated in the United Kingdom and other countries since 1970s to reduce energy consumption during peak hours and to increase plant utilization [6]. DR has been defined as changes in electricity use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [7]. The DR scheme can help the participating customers to save on electricity bills when they reduce their electricity consumptions during peak hour

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and shifting peak time load to off-peak time [8]. Several studies have been focused on peak load energy reduction and DR systems benefits and challenges [9–12]. According to the US Department of Energy, the residential DR programs can be classified into incentive-based programs and price based programs [13]. In incentive-based programs, the utility can access and control the appliances of end users and provide financial incentives for demand reduction during peak hours to participating customers and the consumers get a discount rate for their participation such as direct load control [14]. However, by direct access to control on/off home appliances intrude occupant's privacy and this option is regarded as one of the drawbacks of incentive-based programs [15]. In price based programs, consumers voluntarily modify the power consumption in their houses based on time-based electricity and follow the real time cost of electricity by using tariff price program such as time of use pricing, real time pricing and critical peak pricing [16]. These programs will offer different prices at different times of the day like during off-peak and on peak periods to reflect the ability of the utility to produce the energy needed. Time-of-use pricing is the most common residential electricity tariff and currently considered for execution in many utilities around the world which is divided into time slots at various seasons of the year or hours of the day using smart energy meters [17]. The smart energy meter can provide two-way communication between customers and utilities and the DR signal can offer incentive to customers to make decisions accordingly on electricity consumption [18]. Moreover, the homes have the option to send the status and information about their energy consumption [19,20]. A smart home enabled with residential DR strategies is usually equipped with a home energy management system (HEMS) that manages controllable appliances associated with smart outlets and smart meter [21]. The technology for HEMS is efficient with communication technology, which connects home appliances for remote management based on the internet and a combination of the home network to reduce the peak demand without affecting the comfort of the consumers [22,23]. By using HEMS, the overall electrical appliance loads can be fully automated and controlled with enabled DR programs at the domestic sector [24]. Various studies have discussed the concept and scheduling strategies of smart HEMS [25–30].

In recent years, many decision-support tools and optimization techniques have been applied to help domestic customers in reducing the energy consumption by creating an optimal home appliance scheduling of energy usage based on different pricing schemes and comfort settings. To achieve this goal, there is need to implement smart control in the domestic building. In [31], distributed control algorithms have been applied to schedule home appliances with DR based on the communication network architecture. The genetic algorithm with artificial neural network (ANN) has been applied to schedule home devices and optimize energy consumption in the domestic sector by reducing the demand during peak periods [32]. Hybrid lightning search algorithm based ANN has been used to predict schedule controller in a HEMS [33]. In [34], autonomous demand-side management system based on game theory approach has been developed to optimize the appliances energy consumption and manage residential loads that help homeowners to select the priority of appliances considering either electricity cost reduction or customer comfort. In [35], electrical appliances have been scheduled to reduce electricity cost based on dynamic pricing using robust optimization and stochastic techniques. In a related work in [36], hardware based HEMS incorporating DR has been developed to control the customers household by using a rule based technique. A prototype smart HEMS using machine learning algorithm with dynamic price response has been developed in [36]. A rule based HEMS to control and schedule four home appliances that include water heater, air-conditioner, clothes dryer and electric vehicle considering residential demand response application and rules has been developed in [37]. In [39], a smart plug was developed with Zigbee sensor for measuring and monitoring the power consumption of home appliances in the HEMS. A major issue that is faced in scheduling and shifting user loads is the minimization of the electricity consumption during peak hours without affecting the comfort of occupants. However, most previous researchers focused on reducing electricity bills and saving energy without considering user comfort. Thus, to schedule and control home appliances there is need to take into account all possible challenges, such as comfort level, demand limit and tariff.

This paper presents a new binary backtracking search algorithm (BBSA) based real time optimum schedule controller for HEMS to achieve energy savings and limit the household peak demand in the home on the basis of the scheduled operation of several appliances according to a specific time, resident comfort constraints and priority. Furthermore, hardware smart socket and graphical user interface (GUI) of HEMS are designed and build with Zigbee modules and various sensors are used to control a certain load. In addition, this paper suggested two cases to schedule the home appliances. The first case considers DR signal from 4 to 11 pm on a week day and the second case considers different time of the day at weekend. An average single-family home size 2300-square feet with 5 persons have been considered as a case study in Malaysia. Four appliances, namely, air conditioner (AC), water heater (WH), refrigerator (REF), and washing machine (WM), are considered controllable. To validate the developed BBSA schedule controller the results are compared with the binary PSO schedule controller.

2. Development and design of the home energy management system

The HEMS consists of four devices, which are AC, WH, WM, and REF. The overall system can help homeowners in controlling and monitoring the energy consumption of the appliances by gathering the data from selected loads by utilizing smart socket. The smart socket provides the interface between the developed HEM and the non-smart load appliances in real time. The smart socket is designed to provide remote control of non-smart loads thus providing a practical solution to interface the loads with the developed system and schedule on/off status of selected loads [38]. In the operation of the HEMS, it is assumed that the house is equipped with smart meter which continuously communicates between utility and homeowner and can receive DR signals from the utility. This signal and other user preference conditions are used as inputs to the system to perform local control.

The DR signal with information on the duration, situation and amount of load to be shed is assumed to be received directly from a smart meter in the HEMS. The following subsections describe the required setup of the proposed HEMS (Fig. 1).

2.1. Graphical user interface design

The HEMS includes GUI and associated software to assist customers in monitoring the total and individual power consumption, monitor the on/off status of home appliances, the room temperature, and water temperature for WH as shown in Fig. 2. As depicted in the figure, the dashboard can display the power consumption in (Watt) for each load, the room and water heater temperature in °C, the total power consumption and also the total energy in (kWh). Furthermore, it is possible to turn on/off each home appliance manually from a push button switch display in the developed dashboard.

The proposed software includes the DR algorithm that represents the main controller. In addition, this software is able to collect