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A new real time home power management system

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ABSTRACT

In this work, a real time home power management (RTHPM) scheme and the corresponding rule based control algorithm (RTHPM algorithm) are presented. The proposed system produces a real time solution to reduce the electricity cost and to avoid the high peak demand problem simultaneously for a Smart Home (SH) which is equipped with smart electrical appliances, power units (photovoltaic system, grid, battery), communication network and a Main Controller (MC). In RTHPM system, power unit(s) are prioritized due to their current status and tariff rates. When the prioritized power units cannot provide the home power demand within the predefined grid limits and efficient battery usage rules, MC interferes with the status of appliances as much as it is permitted. The simulation test results show that the proposed RTHPM system significantly reduces the electricity cost and high peak demand.

1. Introduction

Recently, the increase in electricity consumption, its negative environmental impact and limits in production require energy savings and active use of renewable energy sources. Since a big part of electricity consumption occurs in residentals, proper use of electricity in homes plays important role to contribute these requirements.

Throughout the course of a day, home electricity demand varies at different times. When the greatest number of people use electricity, the network overloads and high peak demand takes place. In order to avoid high peak demand, electric utility companies apply different tariffs in different time intervals within the day such as real-time pricing (RTP), time-of-use (TOU) and critical peak pricing (CPP) [1]. With TOU which is considered in this work, electricity prices are lower when the demand is low (off-peak) and higher when the demand is high (on-peak).

Smart Home (SH) is defined as a residental equipped with smart electrical appliances, sensors and distributed power units containing renewable energy sources [2,3]. Due to its structure, SHs can be integrated with home power management systems which monitor and manage electric generation and consumption in the home to reduce energy use, electricity cost as well as to avoid high peak demand.

Recently, home power management has become a very popular subject and much research which focus on different goals has been done on this issue. In [4] which is one of the studies aiming to decrease the total electricity cost, a method that learns the changes in energy pricing and creates a corresponding time schedule was given, while in [5] a distributed energy resource scheduling algorithm based on particle swarm optimization is presented. The authors schedule appliances to minimize the electricity cost by taking the statical price information in [6]. In [7] a dynamic load priority method, in [8] an offline optimization method and in [9,10] a linear approach were proposed to schedule appliances for minimizing the electricity cost. A smart building energy management strategy, based on price variations and external conditions as well as comfort requirements, is presented in [11]. Apart from these works, in [12,13] the instantaneous high peak demand problem was examined. In [12], the peak-average electricity consumption rate was decreased by using a kind of game theory approach while in [13] priorities were defined for appliances and the operations of these appliances were directed according to their priorities in order to keep the power consumption below a pre-defined limit. In some studies such as [14,15], the electricity cost and peak demand values are reduced simultaneously.

Nevertheless, in the state-of-the-art home power management system there is no methodology which produces a real time solution to reduce the electricity cost and to avoid the high peak demand problem simultaneously by controlling the electrical appliances and considering their real power profiles. In this study, Real Time Home Power Management (RTHPM) scheme, which is a power management system providing all these circumstances,

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and the corresponding rule-based control algorithm (RTHPM algorithm) are presented. SH defined herein consists of smart electrical appliances (e.g., air conditioner, washing machine, dishwasher, refrigerator, TV and lights) which are divided into three subclasses as controllable, semi-controllable and uncontrollable, power units (photovoltaic system, grid, battery), communication network and a Main Controller (MC). Power units are prioritized due to their current status and tariff rates. MC communicates with smart electrical appliances and power units periodically. According to the developed RTHPM algorithm, MC selects power unit(s) that will provide the power demand of SH due to their priorities at the current time interval. When the prioritized power units cannot provide the demand within the predefined grid limits and efficient battery usage rules, MC interferes with the operation of semi-controllable and controllable appliances in order to reduce the demand.

The paper is organized as follows. In Section 2, we describe our Smart Home model with its smart electrical appliances and distributed power resource units. In Section 3, we explain our RTHPM scheme in detail. Simulation results are given in Section 4. Finally, Section 5 concludes the paper and highlights future work.

2. Smart home

In RTHPM scheme, SH consists of smart electrical appliances, power units, communication network and MC. In this scheme, one execution period (e.g., one day, 24 h) is discretized into a prescribed number T of uniform time slots, i.e., $t \in \mathcal{T} = \{1, 2, \ldots T\}$, so that the total number of time slots in a day is $T = 24/\Delta_t$ where Δ_t represents the length of each time slot.

MC, the brain of RTHPM, communicates and controls appliances and power units. At the beginning of each time slot, MC gathers the status and power information from appliances and power units. Then according to the developed RTHPM algorithm it decides which power unit(s) should provide the power demand of SH; moreover, when essential MC interferes with the states of appliances as much as it is permitted and also acknowledges the new status to appliances.

2.1. Smart electrical appliances

In RTHPM scheme, three working modes and various program modes are assigned to each appliance $a \in \mathcal{L}$, where $\mathcal{L}$ represents the set of smart electrical appliances (shortly, appliances) in SH. In order to improve user comfort and use the energy more efficiently, each program mode offers different functionality and features, such as operation times, energy consumptions and more. These program modes are allocated by manufacturers to fulfill these functions and features.

The sets of working modes and program modes are represented by $M_w = \{on, off, standby\}$ and $M_p = \{1, 2, 3, 4, \ldots, |M_p|\}$, respectively. The status of an appliance $a \in \mathcal{L}$ operating in a program mode $i \in M_p$ at time slot $t \in \mathcal{T}$ is represented by the status vector which is defined as $\boldsymbol{X}^a(t) = [\boldsymbol{X}^a_w(t)|\boldsymbol{X}^a_p(t)] \in \{0, 1\}^{1\times(|M_w|+|M_p|)}$. Here, $\boldsymbol{X}^a_w(t) \in \{0, 1\}^{1\times|M_w|}$ is the working mode vector at time slot t in which [1 0 0], [0 1 0], [0 0 1] representing *on*, *off*, *standby* working modes respectively. Similarly, $\boldsymbol{X}^a_p(t) \in \{0, 1\}^{1\times|M_p|}$ is the program mode vector at time slot t in which ith element of the vector, $X^a_p(t, i)$, is 1 others are zero when the ith program mode is active. For example, at time slot t the status vector of an appliance which is operating, that is, its working mode is *on*, in program mode 2 through four program modes is $\boldsymbol{X}^a(t) = [1\,0\,0|0\,1\,0\,0]$ where $\boldsymbol{X}^a_w(t) = [1\,0\,0]$ and $\boldsymbol{X}^a_p(t) = [0\,1\,0\,0]$.

In RTHPM scheme, each appliance has its own local controller and power measurement module. The status (working mode and program mode) of an appliance is selected initially by its local controller or the user locally. Thus, either users can select the program mode according to their preferences or high-end appliances can determine their program modes by using their own sensors. The locally selected status request of an appliance $a \in \mathcal{L}$, at a time slot $t \in \mathcal{T}$ is kept as its status vector of the next time slot, i.e., $\boldsymbol{X}^a(t+1)$. If the power sources do not meet the total power demand of SH within the constraints specified by RTHPM scheme (will be explained in Section 3), it is required to reduce the total demand. For this purpose, MC can interfere with the status of appliance a (if it is allowed) and updates the status vector as $\boldsymbol{X}^a_{updated}(t+1)$, then sends it back to the appliance a which operates according to this status vector during time slot $t+1$. Any request of the user or local controller on the status of the appliance a during time slot $t+1$ is kept as its status vector of the next time slot, i.e., $\boldsymbol{X}^a(t+2)$, which will be send to MC at the beginning of time slot $t+2$.

In RTHPM scheme, appliances in SH are divided into the following three subclasses: uncontrollable, semi-controllable and controllable. The set of appliances is represented by $\mathcal{L} = \mathcal{L}_{UC} \cup \mathcal{L}_{SC} \cup \mathcal{L}_C$ where $\mathcal{L}_{UC}, \mathcal{L}_{SC}, \mathcal{L}_C$, are the sets of uncontrollable, semi-controllable and controllable appliances, respectively. Classification of appliances is made based on user comfort and appliance's features. MC's interferences with appliances are realized according to the class of appliances in order not to deteriorate user comfort. These subclasses and their properties will be explained in the following sections.

2.1.1. Uncontrollable appliances

Appliances whose status (both working modes and program modes) effect user comfort directly are classified as uncontrollable appliances, e.g., TV and lights. In order not to deteriorate user comfort, MC can not interfere with uncontrollable appliances. Operations of these appliances are controlled by their local controller according to user preferences, home occupancy and environmental conditions. For example, lights will turn on if the following conditions are met:room is occupied, user's request and insufficient natural lighting exist. When room occupancy or insufficient natural lighting disappears, lights go into stand-by mode in order to save energy. If the user's request is lost, lights will turn off.

The communication structure between MC and an uncontrollable appliance $a \in \mathcal{L}_{UC}$ is given in Fig. 1(a), where, at time slot $t \in \mathcal{T}$, an uncontrollable appliance $a \in \mathcal{L}_{UC}$ sends its locally selected status request as operating in program mode 1 by the status vector $\boldsymbol{X}^a(t) = [1\,0\,0|1\,0\,0\,0]$. Since MC does not interfere with controllable appliances, it does not send any updated status vector to the appliance a and the appliance operates according to its status vector at time slot t.

2.1.2. Semi-controllable appliances

Appliances whose working modes effect user comfort directly are classified as semi-controllable appliances. Thermostat controlled appliances (i.e. water heater, fan heater, air conditioner, refrigerator and etc.) are in this type. MC cannot interfere with working modes of semi-controllable appliances in order not to deteriorate user comfort, but can interfere with their program modes via switching their current program mode to the least power consuming one. For example, a refrigerator with a variable capacity compressor tries to keep cabinet temperature at a set value selected by the user. When the program mode is switched to the least power consuming one, the compressor speed decreases. Therefore, cooling capacity (cooling speed) of the compressor changes to keep the cabinet at the same temperature. Thus, the energy consumption of the refrigerator drops without altering the cabinet temperature.

The communication structure between MC and a semi-controllable appliance is illustrated in Fig. 1(b) where, at time slot $t \in \mathcal{T}$, a semi-controllable appliance $a \in \mathcal{L}_{SC}$ sends its locally selected status request as operating in program mode 1 by the status vector $\boldsymbol{X}^a(t) = [1\,0\,0|1\,0\,0\,0]$. However, MC decides it to operate in program