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Home energy management incorporating operational priority of appliances

Mohammad Rastegar [a], Mahmud Fotuhi-Firuzabad [a,*], Hamidreza Zareipour [b]

[a] The Center of Excellence in Power System Control and Management, Electrical Engineering Department, Sharif University of Technology, Tehran, Iran
[b] Department of Electrical and Computer Engineering, University of Calgary, Calgary, AB, Canada

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ABSTRACT

Home energy management (HEM) schemes persuade residential customers to actively participate in price-based demand response (DR) programs. In these price-based HEM methods, a controller schedules the energy consumption of household's controllable appliances in response to electricity price signals, considering various customer preferences. Although numerous methods have been recently proposed for HEM application, prioritizing the operation of controllable appliances from the customer's viewpoint in price-based HEM has not been addressed, which is the focus of the present paper. To do this, the value of lost load (VOLL) of each appliance is defined to indicate the operational priority of that appliance from the customer perspective. Considering appliances' VOLL, electricity tariffs, and operational constraints of appliances, an optimization problem is proposed to minimize customer energy and reliability costs. The output of the proposed HEM would be the optimum scheduling of household electrical demand. Numerical studies illustrate the effectiveness of the proposed HEM method in a smart home, considering different time-varying electricity pricings.

Introduction

In smart grids, demand response (DR) programs play major roles in activation of end-users participation in the distribution system operation. In DR programs, the distribution system operator designs an electricity tariff or an incentive to convince customers to voluntarily change their daily electrical consumption pattern [1,2]. Since the residential demand is a significant portion of the total system load, residential DR programs are important from the system operator's perspective.

One of the obstacles in widespread application of residential DR programs is the lack of customers' knowledge in responding to the received pricing or incentive signals [3]. One of the proposed solutions is a control system that automatically responds to the received signals by solving a simple optimization problem, which is generally referred to as home energy management (HEM) systems [3,4]. A HEM program typically minimizes the customer's costs, which could be a factor in stimulating customers to participate in DR programs [4,5]. The output of solving an optimization-based HEM problem is the energy consumption schedule of controllable appliances. In addition to controllable appliances, in coming years, plug-in hybrid electric vehicle (PHEV) technologies will expectedly penetrate into smart homes because of their environmental advantages [6]. Since these vehicles have batteries that can be charged in different levels by the grid and can be discharged to return the energy back to the grid (e.g. vehicle to grid capability), it is necessary to incorporate PHEV in the load management procedure. Hence, solving the HEM problem results in energy consumption schedules of households' controllable appliances and charge/discharge scheduling of PHEVs.

Several papers [7–12], have focused on HEM modeling and formulations. The proposed methods in those papers reduce the energy cost for the customer as well as the household's peak load. In addition, to convince customers to actively participate in the DR programs, the customers' comfort is modeled in these works. Some works, such as [13–22], mathematically model the customer inconvenience in addition to energy costs. Models of inconvenience in these works can be classified into two categories: inconvenience as a result of timing, and inconvenience as a result of undesirable energy states. In the former class, a penalty is attributed to delays in the use of devices due to load shifting, such as washing machines and dryers [13–18]. In the latter one, a penalty is attributed to deviations from an ideal energy state, such as the temperature of a house [19–22].

* Corresponding author at: Sharif University of Technology, P.O. Box 11155-4363, Tehran, Iran. Tel.: +98 21 66165921; fax: +98 21 66023261.
E-mail address: fotuhi@sharif.edu (M. Fotuhi-Firuzabad).

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Some works introduce the priority of an appliance for the customer to add another level of satisfaction to implement DR programs [23,24]. In [23,24], the designed DR scheme is to cap the customer's consumption to a predetermined limit. Accordingly, the priority for controllable appliances along with the associated thermal and operational constraints is set in [23,24] to determine which appliances can be turned off in the case of DR implementation. Although the concept of appliances' priority is incorporated in these works, their proposed DR plans do not include price-based DR programs.

In summary, although the concept of proposing an optimization problem for HEM [2–5,8–10] and also incorporating priorities of running household's appliances in DR implementation [23,24] have been presented in the literature, modeling the priorities of appliances in the implementation of HEM, based on price-based DR programs, has not been addressed in the previous works.

In this paper, a price-based HEM framework is designed to incorporate the priority of operating different appliances in the optimization model of an energy management system. As an example, a home may have two controllable appliances, and the operation of one of them for the customer is more important than the other one. This customer should be able to distinguish between these appliances in the HEM scheme. To do this, the value of lost load (VOLL) is determined for each appliance, according to common time-varying tariffs for residential customers, i.e., time of use (TOU) and inclining block rate (IBR). In other words, considering the different tariff rates, the customer determines a value for operation of an appliance. Actually, VOLL value of an appliance shows the importance of running that appliance for the customer in comparison with the electricity cost. Subsequently, VOLL values are used to calculate the customer reliability cost for the next day. Thus, the objective function is to minimize the customer's energy and reliability costs for the next day. The output of the proposed HEM is the scheduled household demand for the next day. In conclusion, the main contribution of this paper is to consider the operational priority of appliances in a HEM model designed for implementation of price-based DR programs. The significance of the proposed method is to add another level of customer satisfaction and flexibility to the existing price-based HEM models.

The rest of this paper is organized as follows. Section 'Methodo logy and Problem Formulation' is dedicated to description and formulation of the proposed method. The method is examined in two designed case studies in section 'Numerical Studies'. The paper is concluded in section 'Conclusion'.

Methodology and problem formulation

Background

In the context of HEM, many works propose a method to minimize the customer costs, satisfying the operational constraints of the household devices. For example, in [7] the optimal scheduling of smart homes' energy consumption is determined using a mixed integer linear programming (MILP) approach. The optimization-based model is proposed to minimize the total day-ahead expense of a smart building's energy consumption. Ref. [8] presents a controller that curtails the peak load as well as saves the electricity cost while maintaining the reasonable thermal comfort associated with heating, ventilation and air conditioning (HVAC) systems at homes. In [9], an automatic energy consumption scheduler improvised in smart meters finds the optimum scheduling based on the received price from the utility. The optimum scheduling is achieved with interactions among the users/customers and the utility company in the energy consumption game. In [10], mathematical models are developed for household appliances, and mathematical optimization models of the residential energy consumption are proposed with the objectives of minimizing energy consumption, total cost of electricity and gas, emissions, peak load, and/or any combination of these objectives. In addition, Ref. [11] mathematically formulates an optimization-based HEM consists of a set of solar photovoltaic modules, a small wind turbine, an energy storage system, an electric vehicle, and a set of controllable appliances. The objective is to minimize the energy costs in the format of mixed integer linear programming from the consumer's perspective.

In summary, the abovementioned works support the idea of proposing optimization-based HEM to facilitate the implementation of price-based DR programs. Neither these works nor other related works in the context of price-based DR programs, present a model to consider the priority of running household's appliances in the optimization procedures. In these works, the importance of all appliances is assumed to be the same from the customer's viewpoint, which may not always be the case in reality. In this section, a HEM model considering the priority of appliances from the customer's viewpoint is proposed to further facilitate the implementation of price-based DR programs. At first, different categories of controllable appliances are introduced. Then, TOU and IBR tariffs as the most popular price-based residential DR programs are mathematically presented. Since VOLL values of controllable appliances have the main role in the proposed method, the manner of determining these values by the controller according to customer's preferences is explained in this section. Finally, the optimization problem, i.e., the objective function and the constraints, in MILP format, is described.

Different categories of controllable appliances

For the proposed HEM scheme, household appliances are divided in two groups, i.e., controllable and uncontrollable appliances. The operation of controllable appliances can be scheduled in the HEM, based on the received prices; while uncontrollable appliances have non-programmable operation time and consumption level. In the following, the controllable appliances, similar to [3,4,13], are partitioned into two categories for modeling in the HEM program.

ON/OFF controlled appliances

Some controllable appliances such as dishwasher, washing machine, and clothes dryer can be controlled in ON/OFF manner. In other words, the energy consumption of these appliances at each operating time step is definite and independent of time, and the operating time steps of these appliances can be determined by solving the HEM problem. This assumption is in line with the proposed model in the literature [3,4,13]. The required time for proper operation of these appliances is assumed as a known parameter in the problem.

Regulating appliances

Controllable appliances such as cooling/heating systems, whose energy consumption level at each time step can be controlled, are named regulating appliances. These appliances can have maximum and minimum limits for their consumption at each time step. In addition, the total daily energy consumption of these appliances is defined as the problem input. It should be noted that PHEV can be accommodated in this category.

Residential electricity tariffs

TOU is the most common residential electricity tariff [25]. In TOU tariff, the electricity price changes in definite levels during