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Implementation of a dynamic energy management system using real time pricing and local renewable energy generation forecasts

Onur Elma, Akın Taşçıkaraoğlu, A. Tahir İnce, Uğur S. Selamoğulları*

Electrical Engineering Department, Yildiz Technical University, Esenler, Istanbul, Turkey

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The advanced communication and control technologies in smart grids enable end users to actively participate in balancing supply and demand in response to electricity tariff changes by controlling their electricity consumption through demand response (DR) programs. In order to further exploit the cost-saving potential in residential houses, home energy management (HEM) systems have gained increasing interest, particularly in the last decade. HEM system basically focuses on the control of home appliances to reduce their electricity usage or to shift the operations of predefined appliances to the periods with lower prices. However, the integration of local renewable generation units to the residential houses considerably complicates the tasks of HEM systems. This study, therefore, proposes a novel dynamic HEM approach capable of integrating both load and source side dynamics into decision-making process. In the new HEM approach, power consumption of appliances, electricity tariff and power from renewable sources are dynamically taken into account with a 5-min time step. A forecasting model is incorporated into the HEM system for better matching of energy consumption to renewable energy generation. The simulation and experimental results show that the proposed HEM system considerably improves cost savings for residential prosumers and can be implemented in real-world applications.

1. Introduction

1.1. Motivation and background

Gradual increase in energy demand and energy prices, particularly in the developed and developing countries, raises the need for further improvement at both electrical power generation side and consumption side. At the generation side, exploiting renewable energy potential can be considered as a feasible and commercially-applicable method while various solutions such as using grid connected storage systems, more efficient energy use in buildings, and implementing demand side management programs, are generally adopted at the consumption side. In this regard, incorporating all these technologies in a common environment has significant benefits from economic and technical points of view for both consumers and utilities. Smart homes with residential power generating units, which have become widespread at the last decade with the emerging of smart grid concepts, can be pointed out as one of the best examples of such advanced systems.

A smart home can be defined as an intelligent home capable of remotely monitoring and controlling electrical appliances. In these homes, a control system, called home energy management (HEM), is generally employed for the purpose of more efficient energy use [1,2]. These homes might be equipped with various local energy generating units, such as wind turbines and solar panels, supported by storage systems, for generating their own energy and even selling the excess energy to the grid if two-way power flow is allowed. Two-way power flow also facilitates the use of different electric tariffs offered by utility companies, such as time of use (ToU), real time pricing (RTP), critical peak pricing (CPP) in demand response (DR) applications [3–6].

The studies on DR applications generally focus on examining the effects of DR applications on power systems [7–14] or on the power usage of large commercial/industrial buildings [15,16] due to several reasons such as: (i) higher contribution of the aggregated power of many buildings or of large buildings on the power system operations, (ii) relatively predictable and controllable characteristics of the aggregated power, and (iii) the lack of the availability of data at the residential level. However, understanding the importance of the contribution of individual houses and appliances on

* Corresponding author.
E-mail address: selam@yildiz.edu.tr (U.S. Selamoğulları).

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the efficiency of DR applications, particularly at the last decade, and also the increasing penetration of local power generation and storage units in houses have directed the studies to DR implementations at residential dwelling and appliance levels. Furthermore, the development of high-technology data collection tools (smart meters, smart plugs, etc.) has paved the way for these studies.

Residential DR applications aim to control the appliances with the objectives of reducing the overall power consumption and transferring high-demands to off-peak hours. These two aims are of great importance for consumers to gain benefits using their appliances based on the variations in electricity tariff. Residential DR applications also help utility companies to maintain short-term balance between supply and demand. Reducing the overall demand by switching off certain appliances or shifting them to off-peak periods, however, might disturb the end-user comfort to some extent. Minimization of end-user comfort violation in residential DR applications while still accomplishing an improvement in power system operations and a reduction in consumer's electricity bills is an important topic from both the system operator and end-user points of view.

1.2. Literature overview

A large number of studies dealing with DR applications has been presented in the literature. Among them, the efficiency of heating, ventilation and cooling (HVAC) units in residential DR programs is investigated in different studies in terms of energy savings [17], peak heating consumption reduction [18–20] and load balancing [21–23]. With similar objectives, the other appliances, such as refrigerator [24], dishwasher [25] and electric water heater [26], are also considered in DR implementations. A combination of various appliances is used in a number of DR applications for a higher controllable power potential. For instance, wet appliances, namely, washing machine, dishwasher and tumble dryers, are considered in residential DR applications [27]. According to their preset priority, high-power appliances in a house, such as space cooling units, water heaters, clothes dryers and electric vehicles (EV), are controlled with a model in Ref. [28]. Similarly, Chen et al. [29] and Fernandes et al. [30] investigate the dynamic and optimal operation of different appliances based on the user-defined preferences and the technical characteristics of appliances. The load controlling operations are carried out to manage the power flow to the house in outage cases in Ref. [31]. Some studies also use load forecasts for more effective scheduling in DR implementations [32,33]. Furthermore, several studies discuss the contribution of customer surveys about the energy usage profiles on the appropriate scheduling tasks [34,35].

Domestic electrical appliances are generally classified into three different groups in the literature according to their controllability: (i) interruptible loads that can be switched off for a short period of time, (ii) shiftable loads that can be programmed to be used in a later period of time, and (iii) non-controllable loads that cause discomfort to the user when controlled. At the last decade, the studies on matching the power generation of local generating and storage units located in or around the smart houses with the consumption of interruptible loads, and on postponing the functioning of shiftable loads to the off-peak hours or to the times in which the energy from renewable sources are high, have gained increased interest. For this purpose, Li and Hong present a model that controls the loads regarding time-varying electricity tariff and stores the energy when the price is low and use the stored energy when the price is high [36]. A mixed integer nonlinear programming (MINLP) model is proposed in Ref. [37] for optimal energy usage in a grid-connected smart home, which has micro cogeneration system and underfloor heating/cooling unit as energy sources, and a battery and a hot water tank as electric and thermal storage system, respectively.

Several studies also investigate the benefits of renewable energy sources on more efficient and cost-effective energy management in smart homes. Considering the forecasting of weather characteristics, Wang et al. examine the DR operation of a residential hybrid renewable energy system, including wind turbines, Photovoltaic (PV) panels and a battery group, to provide energy to a single family house in a stand-alone mode [38]. Incorporating PV output power forecasts, several studies are conducted for the grid-connected homes with PV panels and storage systems [39–41], and in addition to these components, a combined cooling, heating and power (CCHP) system is used in Refs. [42,43].

Similar to the structure used in this study, excluding the smart home and experimental verification, various studies are realized for more effective DR implementations combining PV panels with wind turbines in a grid-connected house [44–46]. Besides, Cagigal et al. investigate DR operation in a real grid connected smart house with controllable appliances with PV forecasts and a battery system [47]. In another smart home system, Lujano-Rojas et al. present a load management method using price forecasts, energy consumption and renewable power generation, in which only one test day with hourly time step is discussed [48].

None of the literature studies given above considers an experimental DR implementation of a smart home with local renewable energy sources. With this objective, only a few studies are available in the literature. Newsham et al. present a method for a smart home with PV array [49], and Karfopoulos et al. employ a model in a smart home including wind turbine, PV panels and batteries [50]. However, both studies consider a grid-independent smart house, which is a relatively easy task and considerably limits the exploitation of renewable sources and batteries. Furthermore, these studies do not take a dynamic energy management into account within a short term time scale. To the best of our knowledge, the HEM algorithm proposed in this paper is the first study dealing with the dynamic DR implementation of an experimental smart home having renewable energy sources and a battery.

Further explanations on the residential demand response implementations and a larger number of related literature studies can be found in recent literature reviews, in which the demand response programs are investigated from the perspective of their economic and operating benefits [51–54], from the perspective of behavioral factors in household demand response participation [55,56], and from the perspective of their role in smart grids [57].

1.3. Contributions

Considering the drawbacks and advantages of the approaches presented in the literature and also the state-of-the-art on this field, a novel HEM approach is presented in this study with four objectives: to minimize the energy cost in a residential smart house particularly by reducing the household consumption when energy prices are high, to maximize the use of renewable energy potential, to reduce the power profiles at the grid side by alleviating peak demand, and to run a dynamic home energy management algorithm. In order for these objectives to be achieved, the balance between the power generation from the local renewable sources and the energy consumption of the appliances in the house is maintained dynamically while avoiding energy purchases at high costs as much as possible. For this purpose, at the generation side, the potential energy from the renewable sources is exploited using a forecasting tool and at the consumption side, the operation of the appliances is proactively controlled in the cases of insufficient generation in response to the existing energy price and taking the