Energy Conversion and Management 96 (2015) 322–329

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Cooperative home energy management using batteries for a photovoltaic system considering the diversity of households

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ARTICLE INFO

Article history:
Received 5 January 2015
Accepted 26 February 2015
Available online 16 March 2015

Keywords:
Home energy management
Short-term load forecast
Battery operation
Energy management

ABSTRACT

Demand-side energy management systems (EMSs) are expected to be used as a method for further balancing the supply and demand of power systems with high levels of renewable energy generation, such as photovoltaic (PV) power. Energy demand and solar radiation must be predicted to realize the optimal operation scheduling of demand-side appliances by a home energy management system (HEMS), including heat pump water heaters, PV systems, and solar-powered water heaters.

This paper presents a HEMS model that controls a residential battery system connected to a rooftop PV system taking into account of energy load and PV generation forecast errors. Forecast accuracy is verified by real HEMS data from 160 households; the impact of forecast errors on household economics is examined. Furthermore, the contribution to the entire power system is examined using the model under the dynamic pricing system.

1. Introduction

HE large-scale deployment of photovoltaic (PV) power generation is expected to allow for the development of a low-carbon society in Japan; however, it is possible that such a large-scale deployment may cause difficult problems in the balance between electricity supply and demand [1]. Energy management systems (EMSs) on the demand side have been regarded as one of the solutions to this problem, and our research group has proposed a decentralized home energy management system (HEMS) that is able to act in conjunction with centralized energy management systems [2]. Our HEMS manages controllable domestic appliances, such as heat pump (HP) water heaters or batteries, which contributes to balancing electricity supply and demand while maintaining the comfort and convenience currently available to consumers.

A HEMS determines the optimal day-ahead operation scheduling of controllable appliances based on the electricity load and solar radiation forecast as well as incentives linked to a dynamic price system. After determining the optimal scheduling, the HEMS then operates the controllable appliances accordingly, reflecting the actual load and irradiation.

In this paper, we propose a HEMS model that can control a residential battery system connected with a rooftop PV system. Our team has already proposed one HEMS model with a heat pump water heater [2]; however, that model used actual load and PV generation data without any consideration of forecast uncertainty. The new HEMS model considers electricity load and PV generation forecasts, performing scheduling 24 h ahead of time and executing the planned battery operation on the target day. Forecast accuracies are verified by real HEMS data from 160 households, and the impacts of forecast errors on household economics are examined. Furthermore, the contribution to the entire power system is examined using the model under a dynamic pricing system.

2. Rerated work

Demand-side energy management has become crucial for integrating renewable energy into grids, and numerous efforts have been devoted to the scheduling of residential loads. Such efforts can be classified by several factors [3], as listed below.

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http://dx.doi.org/10.1016/j.enconman.2015.02.083
0196-8904/

(1) Controlled target appliance
Many studies on the scheduling of storage systems, including residential batteries and pure/plug-in hybrid electric vehicles, have been proposed [4–8], mainly because of the low risk of compromising customer utilities. Recent studies have investigated the possibility of controlling or using time shifting for other residential appliances, such as washing machines, tumble dryers, dishwashers, and electric water heaters [2,8–12]. Castillo-cagigal et al. proposed the management method of washing machines and so on to realize self-consumption enhancement in battery-PV house [8]. Roscoe et al. evaluated the demand response of home appliances and carefully set price elasticity by appliance type [12]. Recently, a control method of freezer and refrigerator cycles was proposed to reduce the peak load [14].
(2) Purpose of management
The purpose of electricity load management includes peak shaving [6], minimizing total fuel cost [9,12,18], and improving the flexibility of using variable renewable generation [7,8,12] in an entire grid. Customer benefit should be ensured whenever the HEMS is used to manage home energy. Most models aimed to minimize household energy costs based on the electricity price given by a wholesale market or utility. Social welfare, which includes benefits for not only the utility but also the customer, was defined as a function of load [5,9,15,16]. Direct load control models [18,19] and a coordinated model [10] targeting peak shaving were also investigated.
(3) Coordinated/uncoordinated management
HEMSs can be either coordinated or uncoordinated. Coordinated HEMSs require aggregators, which consider utilities either with or without dynamic electricity prices, depending on the wholesale market, and allocate the required management to customers [4,10,11]. Uncoordinated HEMSs are based on single transactions between utilities and customers [5,7,9,15,16].
Coordinated management can enable secure management, although it is difficult to establish as a business model. This management has been considered in most previously developed EV or PHEV management models [13]. Uncoordinated management is easily implemented; however, partial optimization may occur due to unidirectional communication between the utility and customers. Mohsenian-Rad et al. proposed a distributed algorithm that requires message exchanges between customers in a game-theoretical setting and confirmed that the algorithm can reduce customer payments compared to uncoordinated management [17].
(4) Consideration of uncertainty
The uncertainties of electricity load [4,5,16], electricity price [7,20], and PV generation [5,7] have been considered in many housing operation scheduling studies in recent years. For example, Roscoe et al. developed a robust energy scheduling algorithm based on the worst case of uncertainty and demonstrated the impact of load uncertainty on social welfare [12].
(5) Stages of a HEMS
When implementing a HEMS, multiple stages should be considered, such as forecasting, scheduling and operation.

Most works have focused on optimal appliance operation scheduling and evaluation of the worst case of scheduling uncertainty. The impact of the gap between forecasted and real data should be analyzed carefully; however, such an analysis is rarely performed [4]. As a comparatively realistic model, Wi et al. developed a smart EV charging algorithm with both forecasting and scheduling stages. The effectiveness of this algorithm was confirmed by measuring 12 EV utilization and electricity loads on a school building with a PV system [5]. Beaudin et al. proposed a rescheduling method using a moving window algorithm for residential power schedulers as a forecast error correction mechanism and to address the issue of short-sightedness [21].

In this paper, we target a stationary residential battery with a PV system and propose the operation model of battery charging and discharging to facilitate the balancing of the power system. With the feasibility of the system in mind, uncoordinated HEMSs without aggregators are developed and the electricity fee sent to customers from the utility is used as a control signal. The proposed model has three stages: forecasting, scheduling, and operation. Forecasting and scheduling are both one day ahead of time, and operation is on the target day. The major contribution of this paper is to propose a sequence of procedures for the HEMS that considers the uncertainty of forecast errors and can examine the procedure by real HEMS data from 160 households. Furthermore, the effects of the proposed HEMS operation is evaluated on not only particular houses but also the entire power grid linked with dynamic price mechanisms.

3. Cooperative home energy management of a battery-PV house

In this section, the proposed HEMS model is discussed. We considered a detached, individual house with both a PV and battery system, as shown in Fig. 1. The price of electricity is provided for each home by a utility, and the aim of the HEMS is to operate the battery at a minimum cost for each house. The management flow consists of three stages, as shown in Fig. 2. First, hourly electricity load and PV generation are forecasted one day ahead of time

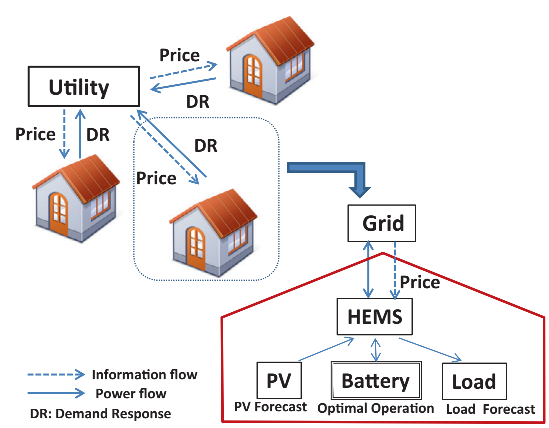

Fig. 1. Cooperative energy management between a utility and households.

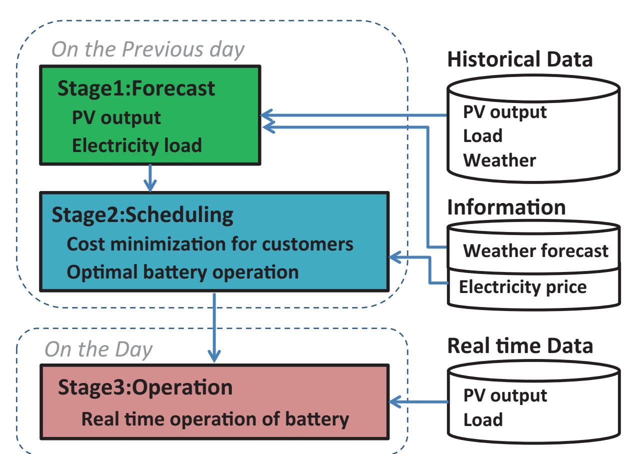

Fig. 2. Energy management flow.