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Distributed real-time demand response for energy management scheduling in smart grid

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ABSTRACT

Demand response is a promising technology to cope with the ever-increasing peak energy consumption in smart grid. For the smart home energy management system, it may choose to charge the battery when the electricity price is low, and discharge the battery to supply the home load when the electricity price is high. Under this circumstance, the temporally and spatially coupled constraints coexist in the energy demand, battery charging and discharging energy, and energy supply. The coupled constraints make the demand response problem more challenging than the existing ones and thus the existing distributed algorithms cannot be employed to find the optimal solution of the problem. In this paper, we focus on the real-time two-way communications between utility company and multiple residential users, and each user is regarded as a smart home energy management system. A distributed real-time algorithm is proposed to find the optimal energy management scheduling scheme for each user and utility company to maximize the social welfare. To overcome the obstacle brought by the temporally and spatially coupled constraints, dual decomposition technique is employed and the primal problem is decoupled into several independent subproblems which can be solved in a distributed way by each user and utility company without revealing or exchanging their private information. Simulation results are provided to demonstrate that the proposed distributed algorithm can bring potential benefits to the society.

1. Introduction

With the development of science and technology, smart grid has been a new trend to replace the traditional power grid [1–5]. The penetration of smart meters [6] and the capability of two-way communications are the main technical setting the stage for demand response merging into smart grid. Demand response is a promising technology in smart grid to cope with the ever-increasing peak energy consumption through peak load shifting, which is conducted by utility company and users to decrease the pressure of power grid and save the power expenses of users [7–11]. Among demand response programs, real-time pricing (RTP) has been regarded as the most efficient and economic price strategy to reduce peak-to-average ratio of demand [12,13].

There have been a lot of studies on demand response in smart grid. The optimal residential energy consumption scheduling with price prediction has been studied in [14] to reach a compromise between minimizing the electricity expenses and the cost of waiting for the operation time of appliances. [15] has proposed a power scheduling strategy for residential users to achieve a trade-off between the payments and the discomfort. [16] has proposed a distributed algorithm to maximize all users' total welfare without revealing each user's private information. Game theory has been adopted to optimal the energy consumption scheduling to minimize the energy cost of utility company and the peak-to-average ratio (PAR) of energy demand in [17]. The distributed real-time algorithms proposed in [18,19] have found the optimal energy consumption levels and energy supply to maximize the aggregate utility of all users and minimize the energy cost of energy provider. It is worth mentioning that [19] has extended the single utility company serving multiple users to multiseller-multibuyer scenario and formulated the demand response problem as a temporally-spatially coupled optimization problem. A Stackelberg game has been adopted to study the real-time pricing scheme in smart grid with multiple retailers and multiple residential users [20]. Two different distributed optimisation algorithms with different communication strategies and a novel real-time pricing strategy have been proposed to solve the optimal energy scheduling problem in [21]. A distributed gradient algorithm is applied to the double smoothed dual function of a demand response problem which aims to minimize the total energy cost of a large number of households in [22]. A fast distributed demand response algorithm based on primal–dual interior method and Gaussian belief

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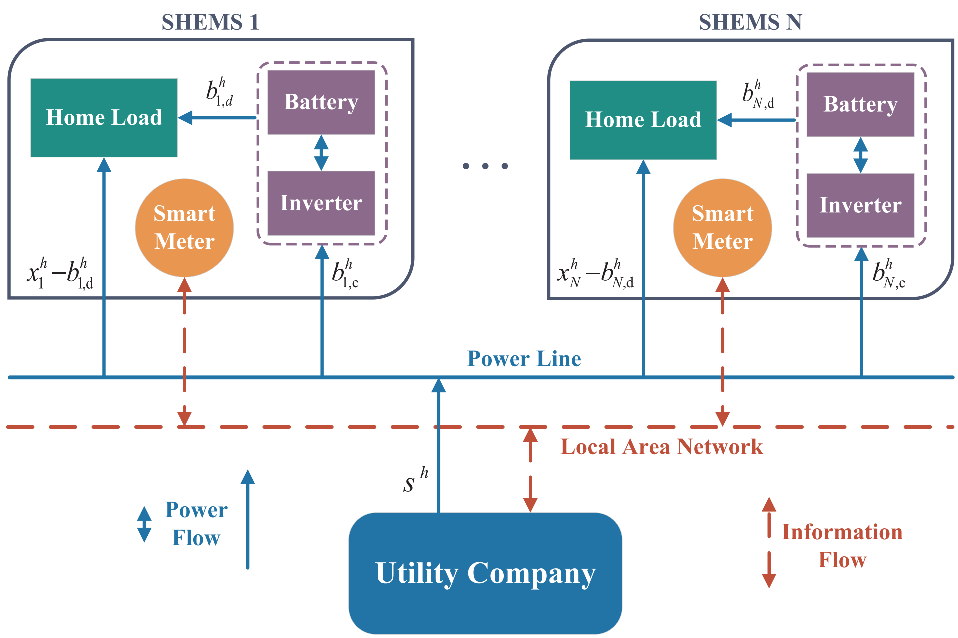

Fig. 1. Block diagram of the system model composed of a utility company, multiple smart home energy management systems, a power line, and a local area network.

propagation solver is proposed to maximize the total social welfare in [23]. Nevertheless, the energy storage system (ESS) has not been taken into consideration in above mentioned works.

Along with the advancement of technology in smart grid, there is a necessary to design smart home energy management system (SHEMS) [24–27]. In accordance with the varying electricity prices, SHEMS plays an important role in scheduling the operation time and mode of each household appliance automatically and economically, including the charging/discharging energy of battery. As an important component in SHEMS, ESS brings benefits to not only reduce the power expenses and demand variations of residential users, but further flatten the load curve and relieve the stress on power grid.

In [28–30], mixed-integer programming (MIP), convex programming (CP) and adaptive dynamic programming (ADP) methods have been introduced into home energy management scheduling, including the charge/discharge cycling of plug-in hybrid electric vehicle (PHEV), battery-assisted appliances (BAs) and multibattery system, to minimize the total cost of customer. [31] has proposed a demand side management framework that incorporates appliance scheduling and power storage to minimize the total cost of customers. However, all of these have ignored the interactions between the energy provider and end users. In [32], different appliances including PHEV and battery have been considered for each household and a distributed algorithm has been proposed to find the optimal prices, consumptions and charging schedules, but it has left the temporally coupled constraint out of consideration.

In summary, none of above works has simultaneously taken both temporally-spatially coupled constraints and ESS into consideration to solve the demand response problem in a distributed manner. Therefore, in this paper, we take both aspects into account to establish the real-time two-way communications between utility company and multiple users, and each user is regarded as a SHEMS. For the SHEMS, it may choose to charge the battery when the electricity price is low, and discharge the battery to supply the home load when the electricity price is high. However, the energy supply, energy demand and battery energy constraints bring both temporally and spatially coupled constraints to the demand response problem, which has not been absolutely exploited in the context of demand response. Thus, a distributed real-time algorithm is proposed to find the optimal energy management scheduling scheme for each user and utility company to maximize the social welfare. Using dual decomposition, the primal problem is decoupled into several independent subproblems which can be solved in a distributed way by each user and utility company at each time slot to locally determine the optimal energy demand, battery charging and discharging energy, and energy supply without revealing or exchanging their private information, respectively. The main contributions of this paper are summarized as follows:

- The energy supply, energy demand and battery energy constraints are all taken into consideration, which make the demand response problem a temporally-spatially coupled optimization problem.
- A distributed algorithm based on dual decomposition is proposed to solve the temporally-spatially coupled optimization problem in a distributed way by each user and utility company at each time slot to locally determine the optimal energy management scheduling scheme without revealing or exchanging their private information.
- The simulation results demonstrate that the proposed distributed algorithm can bring potential benefits to the society. In addition, the distributed algorithm can be applied to the system containing a larger smart community.

The remainder of this paper is organized as follows. In Section 2, we describe the system model and formulate the demand response problem with both temporally and spatially coupled constraints. The primal problem is dually decomposed into independent subproblems in Section 3. Then in Section 4, we present the solutions of subproblems and dual problem, and propose a distributed algorithm to find the optimal energy management scheduling scheme. Simulation results are illustrated in Section 5, and conclusions are drawn in Section 6.

2. System model and problem formulation

Consider a system model with a utility company and a series $\mathcal{N} \triangleq \{1,\ldots,N\}$ of residential users (smart community), and each user is regarded as a SHEMS consisting of the home load, the smart meter, a battery and its corresponding sine-wave inverter. The block diagram of the system model is described in Fig. 1. The smart home energy management systems are all connected to the power line which comes from the utility company, e.g. generators or a step-down substation transformer connected to the power grid. In particular, each smart meter is assumed to have an energy consumption controller (ECC) embedded in it. ECC possesses the capacity of controlling the operation time and