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Demand side management in a smart grid with multiple electricity suppliers

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ABSTRACT

In future smart grids, the electricity suppliers can modify the customers' load consumption pattern by implementing appropriate DSM (demand side management) programs using smart meters. Most of the existing studies on DSM, only consider one utility company in the supplier side. In this paper, the possibility of existing more than one supplier in the smart grid is addressed by modeling the DSM problem as two non-cooperative games: the supplier side game, and the customer side game. In the first game, the suppliers' profit maximization problem is formulated by applying supply function bidding mechanism. In the proposed mechanism, the electricity suppliers submit their bids to the DSM center, where the electricity price is computed and is sent to the customers. In the second game, the customers aim to determine optimal load profile to maximize their daily payoff. The existence and uniqueness of the Nash equilibrium in the mentioned games are explored and a computationally tractable distributed algorithm is designed to determine the equilibrium. Simulations are performed for a smart grid system with 3 suppliers and 1000 customers. Simulation results demonstrate the superior performance of the proposed mechanism in reducing the peak load and increasing the suppliers' profit and the customers' payoff.

1. Introduction

In smart grids, it is an existing challenge to adopt appropriate DSM (demand side management) programs to balance the power supply and demand effectively [1]. DSM program involves actions carried out by the suppliers on the customer side to manage the customers' electrical consumption, usually by shifting load demands from peak to off-peak periods [2]. To motivate customers to participate in the DSM program, the suppliers can implement appropriate pricing schemes such as TOU (time-of-use) pricing [3], and real-time pricing with lower rates during off-peak periods [4]. In smart grids, AMI (advanced metering infrastructure) and smart meters enable suppliers to provide customers with the price data [5]. They also enable suppliers to deploy automated DSM programs to encourage actions by the customer to modify the electrical usage to reduce the peak load [6–7]. Reducing peak load can result in reducing power network losses (e.g., transformer losses, and line losses) [8], and improving the efficiency of the power generation [9]. In this paper, we are interested in investigating how an effective DSM approach would affect the daily load profile of the customers, and how the electricity suppliers would deal with this challenge in a smart grid system.

In the literature, there are several studies that address the DSM problem.

Bahrami et al. [10] propose an approach that include electric vehicles with vehicle-to-grid capabilities. With this possibility, electric vehicles can provide certain services to the power grid, including load shifting and congestion management. This paper models an optimization problem to maximize the agents profit in the system. They consider load shifting possibilities for the vehicle owners in the DSM problem formulation. Setlhaolo et al. [11] study residential demand management through the scheduling of typical home appliances to minimize electricity cost. A mixed integer nonlinear optimization model is built to determine the optimal scheduling of home appliances under TOU electricity prices. This paper also looks into the consumer's inconvenience level by modeling the dissatisfaction that comes with the new schedule. Adika et al. [12] propose a DSM framework that incorporates both appliance scheduling and power storage. In the proposed method, each smart meter uses historical data to model power consumption behavior of the devices and to automatically generate the expected appliances' schedule. The smart meter uses the customers' load

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demand, power supply profile and day-ahead electricity prices to generate a cost effective consumption profiles for all customers. Kinhekar et al. [13] use load shifting DSM technique to schedule controllable devices of both commercial and industrial consumers at various hours of the day. Forecasted load data, pool market price and TOD (time of day) tariffs are used to propose a multi-objective DSM solutions based on integer genetic algorithm. Torriti in Ref. [14] assesses the impacts of TOU tariffs on a dataset of residential users from the Province of Trento in Northern Italy in terms of changes in electricity demand, price savings, peak load shifting and peak electricity demand at sub-station level. The assessment is based on the comparison of time-related electricity consumption, prices and peak loads before and after the introduction of TOU tariffs from a dataset of residential consumers. Atikol [15] studies the difficulties in monitoring the customers' demand or time of using electricity. He reviews the experimental findings about the static and dynamic cooling behaviors of hot water in storage tanks and discusses the possible timer programs to avoid the peak hours. The possibility of applying a timer-controlled DSM program is explored for reducing the peak demand caused by EWHs (electric water heaters). Li et al. [16] propose a real time pricing based DR (demand response) algorithm. They introduce the concept of a UEP (user-expected price) to the DR program, which realizes load shifting, valley filling, and peak clipping by comparing the utility price with the UEP. Energy storage systems are also taken into account in the proposed model. Su et al. [17] give game theoretic framework for Energy internet, the next generation of the retail electricity markets. The envisioned Energy Internet is developed for large number of renewable sources and energy storages. They formulate the key market participants of Energy Internet. Game-theoretic based algorithm is given to clear the deregulated retail electricity market price subject to the system constraints. Wang et al. [18] apply the evolutionary game theory to model the GENCO (generating company)s' bidding game with imperfect information. They consider the adaptive learning behavior of the GENCOs in their model. A bidding strategy is used to determine the price of the market, and co-evolutionary computation is employed to search for the NE in the proposed evolutionary game. Mahmoudi et al. [19] consider demand response as a public good. The proposed scheme involves various DR agreements which cover both long term and short term actions. The DR scheme is modeled as the energy resource of electricity retailers. This scheme allows retailers to decide how to procure various DR agreements from aggregators or large consumers. Sheikhi et al. [20] use game theory and formulate an energy consumption scheduling game for the electric vehicles, where the players are the customers and their strategies are the charging rate of the vehicles. They assume dynamic pricing scheme in their model. The scheduling game model consists of a single utility company serving multiple customers. They use Nash equilibrium solution concept to determine global optimal performance in terms of minimizing the bill costs of the customers.

The residential load scheduling has been studied in several papers [10–20]. However, in the mentioned studies, the supplier side is modeled with only one utility company. Smart grid provides the possibility of existing several utility companies competing with each other to supply the load demand. The key challenge in this paper is to propose a DSM program to tackle the peak load induced by the residential sectors in a smart grid with multiple suppliers. In this model, each household is equipped with a smart meter that can collect the market clearing price data. The interactions between the strategies of customers and suppliers are taken into account to determine the optimal daily load profile and the electricity price. Hence, a non-cooperative game theoretic approach is employed to model the DSM problem. The main contributions of this paper are as follows:

- A novel load scheduling approach is proposed to modify the demand of residential customers. The customers are assumed to be strategic and aim to maximize their daily payoff. The payoff function comprises the satisfaction level of the customers from consuming electricity and the daily electricity bill.
- It is assumed that there exist several strategic electricity suppliers that aim to maximize their daily profit. The suppliers' profit function includes the profit gained from selling electricity and the generation cost.
- A novel approach is proposed for the electricity suppliers to set the electricity price based on the supply function bidding mechanism. In this approach, each supplier has its own supply function that determines the amount of generation regarding to the electricity price. The bidding mechanism enables us to model interaction among several suppliers in the electricity market model in which both customers and supplier sides gain benefit.
- It is demonstrated that the DSM problem can be modeled as two games: the supplier side game and the customer side game. These two games are played simultaneously, and it is proved that each of the proposed games has unique pure strategy Nash equilibrium. In fact, these games are related to each other, and for any arbitrary customers' strategy profile, there exists unique Nash equilibrium for the supplier side game, and vice versa.
- A distributed algorithm is developed to determine both mentioned games Nash equilibrium in which the suppliers and the customers have no incentive to deviate unilaterally. The proposed algorithm determines the optimal load profile and the suppliers' bids to maximize the customers' daily payoff and the suppliers' profit.
- The proposed scheduling approach is simulated on the system with 1000 households. Simulations show that the proposed approach decreases the peak load, increases the payoff of the customers and increase the suppliers' profit in the equilibrium. The performance of the proposed algorithm is evaluated by considering different number of customers in the system. It is shown that the algorithm is computationally tractable and can be used in a smart grid system with high number of customers.

The proposed method of this paper can be compared with the works in Ref. [20]. The problem addressed in this paper is different from Ref. [20] in two respects. First, in Ref. [20], the cost function of the customers is the electricity bill of the customers. They have considered known electricity price in the market. In contrast, this paper considers the interaction between the electricity suppliers and the customers to determine the real time clearing price of the market. Moreover, the cost function of the customers comprises the electricity bill and the utility function of the customers. Second, in Ref. [20], the scheduling game is modeled in a system with only one supplier. Whereas, in our model, we have considered a competitive market consisting of several suppliers. The supply function bidding scheme is employed to model the interaction between the suppliers. A DSM center is employed to manage the data transfer between the customers and the suppliers. The DSM center received the bids from the suppliers, calculates the electricity price and sends the price data to the customers to update their load demand profile strategically. It is also shown that, the proposed DSM game has unique Nash equilibrium for the customer and supplier sides.

The rest of this paper is organized as follows. In Section 2, the system model is described, and the DSM problem is formulated as the supplier side and the customer side games. Besides, the existence and uniqueness of Nash equilibrium are proved. In Section 3, a scheduling algorithm is proposed to determine the Nash equilibrium. In Section 4, simulation results are presented, and the performance of the algorithm is evaluated. Conclusions are