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Bargaining-based cooperative energy trading for distribution company and demand response

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HIGHLIGHTS

- The economic interaction between Disco and demand response aggregator is modeled as a bargaining-based cooperative game.
- The axiomatic connection between the Nash bargaining solution and social optimum is investigated.
- A distributed solution to the problem is introduced to guarantee the autonomy and privacy of participants.
- The bargaining cooperative interaction can benefit consumers and energy providers simultaneously.

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ABSTRACT

This paper studies the energy trading among flexible demand response aggregators (DRAs) and a distribution company (Disco) with self-owned generators. Instead of the conventional non-cooperative game based approach, the trading problem is formulated as a bargaining based cooperative model, where Disco and DRAs collaboratively decide the amounts of energy trade and the associated payments. This cooperative interaction can be beneficial to both Disco and DRAs, by reducing the aggregated peak demand and increasing the potential cost savings. The increased benefits from cooperation are fairly allocated among these participants, based on the Nash bargaining theory. Compared with the non-cooperative game based approach, the proposed bargaining cooperative model can further improve the benefits of Disco and DRAs. Moreover, the bargaining outcome can maximize the social welfare of the system. Considering the privacy and autonomy issues of participants, we utilize a decentralized solution to solve the bargaining problem, with minimum information exchange. Numerical studies demonstrate the effectiveness of the bargaining -based cooperative framework, and also show the improvement of benefits of the system.

1. Introduction

1.1. Background and motivation

With the increasing penetration of distributed generators (DGs) [1,2], distribution networks have become more agile and active than the traditional passive system. Distribution companies (Discos), as load serving entities, are endowed with more diverse supply sources, instead of only purchasing from the main grid [3,4]. Demand response (DR), which aims to exploit the potential demand-side flexibility, is also regarded as an effective and promising approach to facilitating the Disco's active management [5,6]. By shifting or/and curtailing flexible loads, DR contributes in the integration of renewable generations, reduction of Disco procurement costs, as well as in the decrease of peak-to-average ratio (PAR) of the aggregated load curves, which will further lower the grid maintenance cost of Disco.

Derived from distribution level, DR is a natural candidate to directly interact with the Disco in the local area. Especially, the recent proposal of the distribution market creates significant opportunities for the direct trade between Disco and DR at retail level. In the U.S., a distribution-level market platform was initiated to bridge the gap between Disco and distributed resources, as addressed in the New York Reforming Energy Vision (NY REV) [7]. This removes barriers to the participation of small-scale players and also empowers them more freedom to bargain with the traditional dominated Disco. On the other hand, this new business environment also may increase the complexity of stakeholders' interactive decision-making process.

In this distribution-level business paradigm, Disco and DR clusters

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are regarded as independent business entities with autonomy and self-interest. For Disco, its one key issue is to optimize the power purchase from various energy resources (also including operating its self-owned energy devices if any). The other issue is to induce customers to change their consumption patterns through appropriate reimbursement (or through retail rate designing). For autonomous consumers, they will only change their original preferred consuming behaviors if such interactions lead to reduced electricity bill (or additional benefit). If the incentives are insufficient, customers may not be willing to respond to the Disco's price/incentive signal. On the contrary, if the incentives are exaggerated, this may jeopardize the retail profit of Disco. Therefore, the critical issue in the interactive trading between Disco and DRs, is how to design the economical signal to induce their mutually beneficial coordination.

1.2. Literature review

Many researches have been carried out on the DR at different system levels, including wholesale level (such as demand bidding, ancillary markets) and distribution/retail level (such as smart pricing, direct load control). Since the purpose of this paper is to investigate the economic interaction between Disco and DR clusters, hereinafter, we mainly review the work on the distribution/retail level. According to the time scale, the literatures on the interaction between Disco and demands can be further classified into three categories: long-term horizon, medium-term horizon, and short-term horizon. In this work, we focus on the dynamic interaction in the short-term horizon.

The retail-level interaction between Disco and DR clusters, in essence, is the Disco and demand sides rationally interact with each other by exchanging the price/incentive and demand information. The most direct approach is that the Disco remotely controls the energy consumption of users based on forward agreements, i.e., direct load control [8,9]. However, this central approach always incurs significant computation burden and privacy problem. Moreover, the customers in this paradigm are always involuntary, and it cannot reflect the dynamic relation between economic signals and demand behaviors. Alternatively, Safdarian et al. [10] utilized the elasticity coefficients to capture the customers' behavior in response to hourly-varying sale prices. According to the external grid prices, Disco determined the commitment of DG and the hourly sale prices to consumers. Similarly, Jin et al. [11] also modeled the relationship between demand and price by elasticity coefficients. With generation capacity, the MG retailer needed to design both retail rates and DGs' operation strategies. Ghazvini et al. [12] introduced the behavior function to model the response of end-users toward the retailer's incentives. Not just seeking to maximize the daily profit, the retailer also tried to minimize the peak demand to avoid capacity tag. Nevertheless, the model in [12] only focused on the curtailable loads, failing to capture the behavior of those shiftable loads. Nojavan et al. [13] also introduced price function to characterize the dynamic relation between clients' demands and sale prices. The objective of the retailer was to determine the retail prices and procurement schedules from various energy sources, to maximize its daily operation profit. However, the above works are mostly implemented from the perspective of Disco (or retailer), rarely analyzing the rational actions of customers. Meanwhile, the economic signals in above approaches are uniformly for all consumers, without considering the differentiated incentives for different loads. This could cause a "herding phenomenon" [14], i.e., all flexible consumers may shift their loads to low-price periods, which may lead to new demand peaks.

Considering the self-interest and information privacy of Disco and customers, the game theoretic approach provides a natural model to study their interactions and outcomes in a distributed manner [15]. Available works on game theoretic interaction between Disco and DR cluster mainly adopted non-cooperative game theory-based approach. In [16,17], the interaction between a retailer and devices was formulated as a one-leader and *N*-follower Stackelberg game. By updating real-time prices, the retailer indirectly controlled various loads to achieve the system optimum. Safdarian et al. [18] also presented a bi-level problem, where the upper sub-problem sought to flatten the total load profile and the lower sub-problem minimized individual customers' energy expenses. In [19], a two-level differential game was proposed to model the framework between autonomous DR and utility, on the premise that the dynamic systems can be modeled using differential equations. Afterwards, with the advent of DGs, many recent works additionally discussed the optimal schedule problem of Disco (or load serving entity). In [10,20–22], Disco was assumed to possess some DERs and also can trade with the upper-level wholesale market. The interaction between the Disco and its customers was formulated as a bi-level optimization problem, and the optimal prices for the demand response were exchanged between the two-level sub-problems, to induce the optimization problem to converge at a Nash equilibrium point.

The above non-cooperative game theory-based approaches enable participants to individually and cost-efficiently make their decisions. However, these strategies fail to capture the potential collaboration among Disco and customers, and thus usually lead to non-Pareto optimal solutions [22–26]. Meanwhile, the Nash equilibrium of a non-cooperative game is generally not social-optimal [22–24]. In other words, the schedule results obtained from Nash equilibrium may not achieve the social welfare maximization, or cannot guarantee fairness of the resource allocation. Instead, the cooperative game theory has an advantage to improve the Pareto-optima and social-optima of the interactive system, since the involved entities are collaborated. The use of cooperative games enables a coordinated load management among the users, subsequently lead to a more efficient load distribution and lower costs for the utility operator. Rieger et al. [14] estimated the benefits of cooperation can offer to households and energy providers.

As one branch of cooperative game, Nash bargaining theory was also applicable to the cooperative interaction problem. Nash bargaining theory has been extensively used in the field of communication network [24], to improve the Pareto-optima and social optimal of the interactive system. Recently, in the electrical engineering field, some works have also been done to improve the performance of the group interaction, resorting to the Nash bargaining theory [26–33]. In [26], the Nash bargaining theory was used to coordinate the cooperation between storage units and the aggregator; the scheme can motivate the rational participants to behave in a socially optimal manner. In [27], the Nash bargaining theory was introduced to encourage the cooperative planning among interconnected microgrids, to achieve a socially optimal planning. In [28], the Nash bargaining-based mechanism was designed to propel the joint optimization among interconnected microgrids, instead of utilizing the conventional Stackelberg game. In [29], the Nash bargaining theory was also employed to explore the cooperative relationship among multiple MGs. In [30], the economic interaction between the distribution system operator (DSO) and microgrids was modeled using the Nash bargaining theory, where players were coordinated to minimize the peak ramp. In [31], the Nash bargaining was incorporated to stimulate the cooperation among urban buildings, to achieve the increased self-sufficiency and reduced carbon emissions. In [32], the wholesale price negotiation problem between a generation company and multiple utility companies was formulated as a bargaining model. In [33], the interaction among the data center operator and tenants was modeled by using Nash bargaining theory, and derived the solutions that are Pareto-efficient.

Compared with the frequently-used non-cooperative game or Stackelberg game, the Nash bargaining cooperative game can yield a Pareto-efficient and fair outcome, and also effectively improve the economic benefits of players. Meanwhile, in the Nash bargaining-based framework, the social optimal solution can be achieved, without jeopardizing the participants' original interests in non-cooperative state. Hence, those self-interested entities are incentivized to cooperate and operate at the social optimum.