RESEARCH ON BIDIRECTIONAL DECISION-MAKING FOR LOAD AGGREGATORS PARTICIPATING IN MARKET TRANSACTIONS AND LOAD DISPATCHING

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ABSTRACT

To provide opportunities for adjustable customers to participate in wholesale electricity market, which are unutilized due to their small and medium-scaled capacity, and to maximize the interests of relevant market participants, a bidirectional decision model for LA considering the information of wholesale market and the availability of adjustable customers is proposed. The market layer makes the market bidding strategies for LA, which seeks to maximize LA's payoff for participation in electricity market, the customer layer arranges the load-shedding plans for customers, to minimize LA's scheduling cost, thus to provide a reference for LA's bidding and dispatching. Simulation results show that the proposed model is valid. And the great benefits brought by LA's participating in the markets shows the necessity of promoting LA in domestic electricity market.

INTRODUCTION

Load aggregator (LA) is the market participant that emerges to develop the potential response capability of the medium and small-scale customers that enables the aggregated load to meet the performance requirement and minimum permits in whole-sale market such as minimum interruptible capacity. LA may participate in market competition as the representative of the customers and achieves economic benefits through providing various types of service. At present, theoretical study and practical applications have been observed in some countries and regions abroad[1] while the re-search of LA in China is still at the beginning stage.

In research paper [2], Cournot game model taking into account generation resource providers, ISO and demand response(DR) aggregators is built up, and the equalized solution is developed for the wholesale market with DR aggregators' participation. In research paper [3], a tree-type market structure is proposed so as to combine the mechanisms of conventional concentrated optimization and distributed participation for DR, and the feedback of price and response is transmitted by LAs among generation resources providers, ISO and customers. The feasible solution is then derived through Lagrange loose algorithm. A layered model of DR participation with LAs operating as media is built up in paper [4], and the study target is then converted into developing the solution to a multi-objective optimization problem based on the assumption that the market with participation of DR resources is completely competitive. The transaction of day-ahead energy market is optimized from the perspective of ISO in paper [5]-[7]while in paper [8]-[11], the optimization is performed from the perspective of power companies so as to realize either minimum electricity purchase cost or peak shaving through load transfer or DR schedule developed by LA.

It may be observed that in the present research, the hourly schedule for LA is developed from the perspectives of ISO, dispatching entity or power company to achieve minimum electricity purchase cost or to reduce risk of electricity purchase while the detailed DR resources dispatching schedule for each customer is proposed by LA to realize the maximum profit. As a new entity in the wholesale market, LA is required to make the bidirectional decisions of both market-side and customer-side rather than solely develop the detailed DR resources dispatching schedules from the perspective of the customers.

In fact, as the interface between market-side and customer-side, LA need to make market-side strategy of bidding in accordance with the dispatch feasibility of the loads. Meanwhile, LA needs to develop DR resources schedule based on market information analysis so as to realize the maximum profit according to the response contract signed with the customers. The bidirectional decision making of both market-side and customer-side for LA to participate in wholesale market is seldom involved in the present research. In this paper, the bidirectional decision making model for LA participating in bidding in day-ahead wholesale market and DR resources scheduling is built up based on market prediction and load dispatching feasibility with the impact of multiple LAs' participation in wholesale market on market price taken into account. The model is expected to provide guidance for LA to make the optimal bidding decision in transactions and assist LA to develop the feasible and efficient customer-side dispatching schedules.

1 ASSUMPTIONS AND MARKET FRAMEWORK

1.1 Assumptions

LA signs the load curtailment contract with the customers and acquires the right of managing a certain quantity of loads, which enables LA to realize unified control of the customers adopting similar demand response strategy and compensation standard. It is assumed in this paper that LA only controls the interruptible load specified in the customers' contract while the payment of the customer's ordinary electricity consumption is made to the retailers or utilities. In addition, it is assumed that signal receiving, device management and data transmitting are completed automatically through control and communication devices installed at the customer side. The customers deliver the demand and metering information to LA while LA delivers the signals of electricity price, motivation and on/off control to the customers.

LA proposes the load curtailment of each customer and evaluate each customer's demand response based on the metering data. The corresponding reward or penalty[1] will be imposed on the customers.

This paper is to maximize economic benefits of LA that manages adequate demand response resources. The quantity and constraints of the customers will be considered during the development of bidding strategy so as to ensure the customers' opportunities of participation in wholesale market with their intentions being protected.

1.2 Market framework

In this paper, specific market operators are assigned to implement the bidding and price matching for DR resources, and the layered framework is established for LA's participation in day-ahead wholesale market. The participants in the layered framework include DR resources purchasers, DR market operators, LA and customers. DR resource purchaser may be ISO, generation company or power company. Market operator is the entity that manages DR resources bidding and price matching. It links DR resource purchasers with the eligible resources managed by LA. Market operator provides DR purchasers and LA with clearance results and helps the transaction of the electricity. Market operator may be ISO or specific organization assigned. Figure 1 illustrates the entities in the market framework and the streams of cash, electricity and information among the entities.

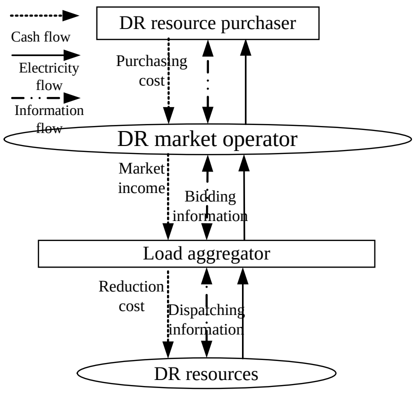

Fig.1 Framework of the electricity market with LA's participation

When LA manages a variety of DR resources with various capacity, price and performance, it may be able to participate in the wholesale market. After submitting the hourly bidding price and capacity to DR market operator, LA may win the bid and receive payment based on the spot-price of electricity, and the customers implementing load curtailment may then be compensated according to the contract. Therefore, the decision objective for LA is to maximize the economic benefits which may be represented by the difference between the income from the market and the compensation fee paid to the customers for load curtailment.

2 BIDIRECTIONAL DECISION-MAKING MODEL

The decision model built up in this paper is to provide bidirectional decisions of market-side and demand-side for LA's participation in wholesale market. At the day-ahead market-side, LA develops the bidding strategy based on load prediction, electricity price and analysis of the impact of DR resources' participation in wholesale market on load and electricity price to realize the maximum interest. At the customer-side, LA proposes the dispatching schedule of DR resources based on evaluation of the constraints and compensation agreement of each customer so as to realize the minimum purchase cost of DR resources. As the dispatch schedule of DR resources is determined, LA develops the practical optimal bidding strategy through rectifying the deviation between the initial bidding strategy and dispatching schedule of DR resources. Figure 2 illustrates the bidirectional decision-making strategy of LA.

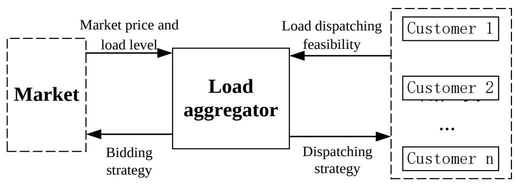

Fig.2 Bidirectional Decision-making of LA

2.1 Bidding decision-making model of market-side

As LA participates in day-ahead wholesale market, it achieves economic benefits through electricity transactions with DR resource purchasers. LA's bidding decision is optimized to realize the maximum economic benefit which are mainly determined by electricity price and cost of compensation for the customers. Therefore, to develop the optimal bidding decision, LA needs to predict load level and electricity price in addition to taking into account the constraints of DR resources operating limits and market rules. According to the statistical results of electricity price and load for PJM day-ahead market[12], the average electricity price varies linearly with load level.

$$P_{mkt}{}^{t} = f^{t} L_{\Sigma bas}{}^{t} = K^{t} L_{\Sigma bas}{}^{t} + b^{t} \quad (1)$$

Where, K^t is the price-load coefficient; b^t is the constant;

$L_{\Sigma bast}{}^{t}$ is the base load; $P_{mkt}{}^{t}$ is the electricity price.

When multiple LAs aggregate dispatchable DR resources to participate in the wholesale market, the electricity price especially that during peak hours may be influenced considerably. It is therefore crucial for a LA to take into account the market price variations attributed to bidding of the LA itself and the other LAs, which requires the LA to predict the bids of the other LAs prior to the bidding decision-making.

The bidding decision-making model with the optimization objective of maximizing the LA's economic benefits is built up upon overall consideration of the factors involved above. In the model, LA_i and LA_j represent the LA of concerns and the other LAs participating in the bidding.

$$Max\sum_{t\in NT}(P_{mkt}{}^{t} * L_{LAi}{}^{t} - f_i{}^{t})$$
$$= \sum_{t\in NT}[K^t(L_{\Sigma bas}{}^{t} - L_{LAi}{}^{t} - L_{LAj}{}^{t}*) + b^t]\bullet L_{LAi}{}^{t} - p_i{}^{k-1}\bullet\sum_{t\in NT}L_{LAi}{}^{t} \quad (2)$$
$$s.t.$$
$$L_{LAi,\min} \le L_{LAi}{}^{t} \le L_{LAi,\max}$$
$$L_{LAi}{}^{t} + L_{LAj}{}^{t}* \le 0.25 L_{\Sigma bas}{}^{t}$$

Where, the first factor is the income based on the spot-price of electricity, $L_{LAi}{}^{t}$ is the decision variation presenting the hourly bidding strategy of LA_i, while $L_{LAj}{}^{t}$ is the hourly bidding strategy of the other LAs; the second factor f_i is the total reduction cost at hour t, $p_i{}^{k-1}$ is the average unit-capacity load curtailment cost during the previous round of iteration. $L_{LAi,min}$ and $L_{LAi,max}$ are the upper and lower bound of the hourly bidding strategy. In this article, the lower bound is 0, the upper bound is the sum of the load curtailment quantity in the contracts controlled by LA_i. Besides, according to the rules in PJM[13], the upper proportion of the DR resources participating in the whole-sale market is set to be 25% of the total load, which is the second constraint in this bidding decision-making model.

2.2 Decision-making model of DR resources dispatching

Customer-side resources usually raise the requirement of their fundamental load service, which makes them unable to be interrupted freely. The contracts signed by LA and the customers need to cover compensation standard and identification method for load curtailment, the minimum and maximum duration of each load curtailment as well as the maximum quantity of load curtailments per day. To ensure the customers' effective response, LA need to provide the customers with the hourly dispatch schedule for DR resources in advance and make reasonable allocation of the bidding electricity among the customers. Due to the fact that the characteristics and cost for load curtailment of the customers differ significantly from each other, LA has to optimize the combination of DR resources based on the contracts so as to reach the minimum cost for purchasing DR resources.

The objective function of LA_i's customer-side DR resources dispatching is presented as below.

$$Min\ f_i = \sum_{t\in NT}\sum_{k\in N_i}(C_k{}^{t} * q_k{}^{t} u_k{}^{t}) \quad (3)$$

Where, N_i is the quantity of LA_i's contracts; $C_k{}^{t}$ and $q_k{}^{t}$ are LA_i's price of compensation and amount of load curtailment for customer k at hour t; $u_k{}^{t}$ is the binary variable that represents whether the load curtailment is activated for customer k at hour t.

In addition, the following constraints need to be satisfied.

The total DR resources scheduled for time segment t should be no less than the bidding capacity.

$$\sum_{k\in N_i} q_k{}^{t} u_k{}^{t} \ge L_{LAi}{}^{t} \quad (4)$$

The limits of the minimum and maximum duration of load curtailment are described as below.

$$\sum_{t'=t}^{t+D_k{}^{\min}-1} u_k{}^{t'} \ge D_k{}^{\min} i_k{}^{t} \quad \forall k, \forall t \quad (5)$$

$$\sum_{t'=t}^{t+D_k{}^{\max}} e_k{}^{t'} \ge i_k{}^{t} \quad \forall k, \forall t \quad (6)$$

Where, $D_k{}^{min}$ and $D_k{}^{max}$ are the minimum and maximum duration of load curtailment for customer k respectively; $i_k{}^{t}$ and $e_k{}^{t}$ are the binary variables that represent the start and end of load curtailment for customer k.

The maximum times of the allowable interruptions:

$$\sum_{t\in T} i_k{}^{t} \le M_k \quad \forall k \quad (7)$$

Where, M_k is the maximum times of the allowable interruptions for customer k of LA_i per day.

The detailed hourly load curtailment schedules of the customers managed by LA may be obtained through the solution of the model presented above. LA need to adjust its bidding strategy based on its DR resources so as to reduce the deviation of the bidding decision from DR resource dispatching schedule and obtain the optimal bidding decision finally.

2.3 Procedures of solution

Figure 3 illustrates the dynamic process of LA's bidding decision-making.

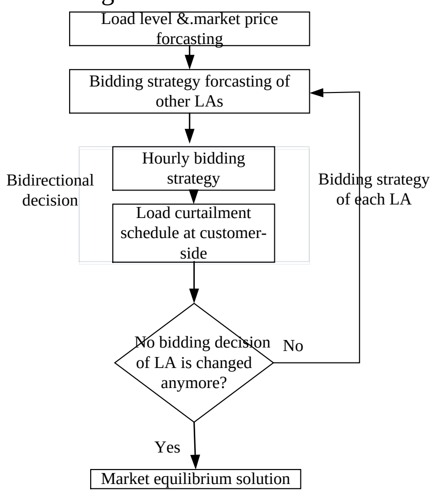

Fig.3 Dynamic decision-making process for LAs

LA makes the bidding decision and develops DR resources dispatching schedule based on its prediction of load level and DR resource price as well as the estimation of the other LAs' bids When the other LAs also make their bidding decisions and participate in the market, the load level is affected accordingly. Such iterative solution procedures will be repeated until market balance is reached and no bidding decision of LA is changed any more. The optimal bidding decisions and DR resources dispatching schedules are then obtained.

3 COMPUTATION TEST

3.1 Data source and assumptions

The load data of PJM market[14] is taken for simulation test of the bidirectional decision-making model. Price-load factor K^t is set to be 0.3 while the constant b^t is set to be 0. The load curtailment and compensation price for the customers of LA_i and LA_j are listed in Table 1. The minimum and maximum duration of load curtailment as well as the maximum times of load curtailments per day are also provided. The load curtailment involved in Table 1 refers to the sum of curtailment for a large quantity of medium and small customers with similar characteristics and aggregated in the contract. The price of compensation for unit-capacity load curtailment is determined through coordinative counseling of LA and the customers during contract signing, and it is not related to the actual amount of load curtailment.

Tab.1 Data of LAs' contracts

Contract No.	Contracts of LA_i		Contracts of LA_j	
	curtailment (MW)	compensation ($/MW)	curtailment (MW)	compensation ($/MW)
1	80	63.32	80	64.76
2	40	43.17	40	57.56
3	60	71.95	65	54.68
4	50	69.07	55	63.32
5	70	64.76	45	71.95
6	20	60.44	35	59.00
7	30	59.00	25	60.44
8	10	61.88	15	61.88
9	1	64.76	5	63.32
10	5	63.32	1	64.76
total	366	-	366	-

As a mixed integer planning (MIP) problem, the bidirectional decision-making may be solved by MIP tools. The decision-making solution provides the total hourly bidding capacity, combination of the contracts as well as the detailed schedules of the start and termination for each contract to be activated.

3.2 Computation results

Figure 4 illustrates the hourly bidding and dispatching schedule for LA_i along with the effect of load curve improvement. The height of the column chart represents the total bidding capacity of LA_i of each hour while the various colored blocks represent the optimized combination of the contracts. In addition to the bidding and dispatching schedules, the effect of the load curve improvement brought by LA's participation in the wholesale market is presented. The bidirectional decision solution enables the customers' requirement on duration of load interruption to be satisfied and ensures the influence on the customers be controlled effectively. In addition, the overall load curve may be improved significantly.

Figure 5 demonstrates the bids of LA_i and its opponents. The average cost of load curtailment is calculated to be 63.03$/MW while the weighted cost of load curtailment determined according to the contracts is 61.88$/MW. As shown in Fig.5, the market price exceeds the weighted cost of load curtailment after 10:00 and triggers LAs' load curtailments. LAs may gain profit accordingly. The variation tendencies of the LAs' bidding dec isions with respect to time are observed to be consistent, which is mainly determined by the overall system load curve.

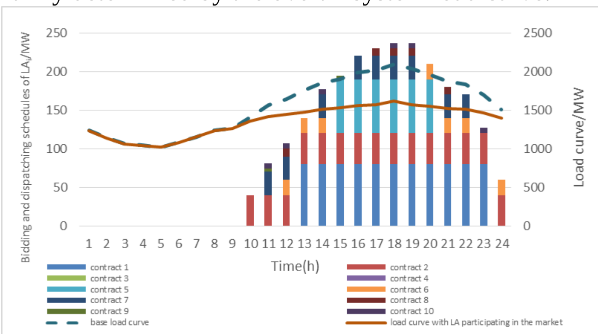

Fig.4 Hourly schedule for load curtailment and the improvement of load curve

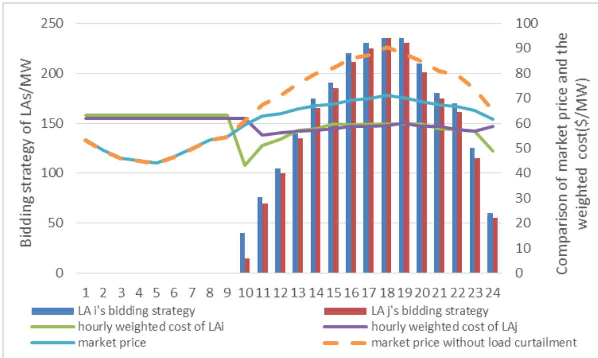

Fig.5 Decision-making results of LAs bidding

3.3 Impact analysis of LA's participation in the market

Figure 6 illustrates the impact of LA's participation in wholesale market on the hourly economic benefits.

The height of the column chart represents the income LA_i gains from the market. The red part of the column chart indicates LA_i's dispatching cost paid to the customers for compensation while the green part indicates LA_i's net benefit determined by the difference of the income and dispatching cost.

It may be observed in Fig.6 that both the benefits obtained by LA_i from the market and the compensation received by the customers increase as the load level rises. Meanwhile, the electricity price during peak hours may be dampened due to load curtailments, and the corresponding electricity purchase cost of the power companies may be alleviated effectively. Therefore, LA's participation in the wholesale market may bring benefits to customers, LA, power companies and also contribute to the improvement of the system load curve. It is crucial to develop incentive policies to promote various customers' participation in the wholesale market through LA and provide healthy environment for LA.

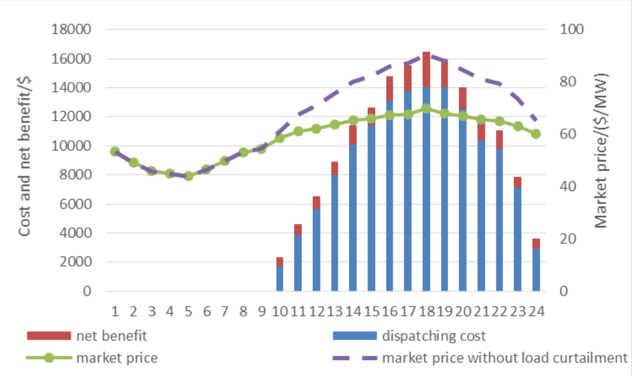

Fig.6 Benefits analysis with LA participating in the markets

4 CONCLUSIONS

In this paper, the bidirectional decision-making model of LA's bidding and dispatching is established based on market prediction and considerations of the customers' constraints. The market-side bidding decision employing the optimization objective of maximizing the net benefits of LA is made based on system load prediction and analysis of the impact of LA's participation in the market on system load level. The customer-side day-ahead dispatching schedule with the optimization objective of minimizing cost is made in accordance with the dispatchable DR resources and the constraints pre-specified in the contracts and delivered to the customers in advance so as to ensure the impact of load curtailments on customers' normal operation be minimized.

The simulation test confirms the validity of the bidirectional decision-making model in forming the hourly bidding decisions for LA's participation in the wholesale market and the dispatching schedules for DR resources. The model employing LA as the interface of information exchange between the customers and market operators to be reduced significantly and alleviates the difficulty of problem-solving effectively. The customer-side resources' participation in the market may bring benefits in multiple aspects. To exploit the profound DR resources market, it is crucial to support and promote the development of LA's participation in the wholesale market.

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