Bidding Mechanism of Aggregated Buildings with Various Flexible Loads Participating in Demand Response Market

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***Abstract*—With the rapid growth of renewable energy resources, the regulation potential on the demand side is being harnessed to address the challenges of supply-demand balance. Buildings consume a significant proportion of electricity and possess various flexible loads, thereby they are regarded as the important participants in the demand response market. The market aims to determine appropriate regulation capacity and clearing price under different scenarios. However, the regulation costs of buildings vary with regulation capacity, and they need to be aggregated to satisfy the participation requirements, so an efficient bidding mechanism should be developed to coordinate the interests of both aggregators and buildings. At first, the piecewise model on regulation costs and regulation capacities is developed to indicate the variable relationships. Then, the bidding mechanism for buildings is proposed to generate the capacity-price curves, which can guarantee the regulation profits by regarding the maximum value as the price at different intervals. On this basis, the bidding mechanism for aggregators is proposed to formulate the capacity-price profiles, followed by the profits allocation method. Not only the aggregation complexity with lots of couples of capacities and prices is simplified effectively, but also can adjust profits between aggregators and buildings in accordance with practical situations. Lastly, the case study is conducted to prove the effectiveness of the proposed bidding mechanism, and the profits allocation method is also discussed to analyze its contribution to regulation performance.**

Keywords*—Demand response, electrical market, buildings, flexible loads, capacity-price curve

I. INTRODUCTION

To achieve the objective of "carbon peaking and carbon neutrality", the rapid growth of renewable energy resources (RES) has been witnessed in China in recent years [1]. According to the statistical data from the National Energy Administration, the newly installed capacity of wind turbines (WT) and photovoltaics (PV) has reached to 120 million kilowatts in 2022 [2]. However, the intrinsic intermittent, fluctuating, and random nature of RESs poses additional challenges in balancing real-time electricity supply and demand. With conventional units gradually replaced by RESs, the flexible loads at the demand side attract more and more interest to provide various ancillary services, called demand response (DR) [3].

Buildings in cities consume a significant proportion of electricity and the electricity demands are increasing steadily, which makes buildings have dramatic regulation potential [4]. On the other hand, buildings are also the natural aggregators of flexible loads, e.g. thermostatically controlled loads (TCLs), electric vehicles (EVs), and battery energy storages (BESs) [5]. Consequently, buildings are regarded as promising participants in the DR program.

With the rapid development of the electricity market in China, the DR programs are marketized in many provinces, which require the participants to submit their capacity-price curves with regard to their own regulation capacities and costs [6]. Through the day-ahead DR market, the power system operators can determine the regulation capacities provided by flexible loads, so as to dispatch multiple regulation resources with the aim of economical operations [7]. Besides, the DR market also contributes to pricing the regulation capacities of flexible loads more appropriately under different conditions. To this end, a DR mechanism of the electricity spot market is proposed to help users participate in the bidding process without price, which is suitable for the early stage of the DR market [8]. However, with the development of the DR market, users are also required to submit prices in some provinces in China. For instance, the interruptible loads transactions will be organized when power systems facing electricity shortages in Guangdong province, the participants are required to submit their capacity-price curves in advance, and the final regulation capacities and prices will be determined by centralized market clearing [9].

Under such circumstances, a proper bidding mechanism is of great importance. Firstly, the capacity-price curve should cover the regulation costs of flexible loads, which consist of the loss of thermal comforts, extra waiting time, and so on [10].

Nevertheless, the regulation costs are always regarded as a constant value, e.g., several flexible loads are equivalent to virtual energy storage, which are coordinated with BESs to participate in the ancillary service market to maximize their profits [11]. In fact, various flexible loads in buildings have different regulation costs, and the different regulation capacities of the same load also result in different costs. Taking the TCL as an example, the thermal comforts are not affected observably within 1 ℃ fluctuations, however, the thermal comforts may be influenced dramatically once the increase of temperature reaches 2 ℃, which will lead to much more regulation costs [12]. Generally speaking, the costs of per regulation capacity are growing with the increase of cumulated regulation capacity. Hence, how to formulate the capacity-price profiles with full consideration of variable costs should be solved to ensure buildings' interests.

Moreover, most buildings need to be aggregated to participate in the DR market according to requirements on minimum response capacity. e.g., 5 MW in Guangdong province [9]. In existing research, aggregators mainly focus on the bidding strategy to earn more returns in the market. The optimization problem on EVs is constructed to provide frequency regulation services for power systems in [13]. Nonetheless, the specific bidding profiles provided by buildings are not involved in the aggregation. In terms of aggregators, the generated capacity-price needs to indicate the costs differences of buildings without losing operability, considering there are lots of groups of prices and quantities from massive loads. Besides, the aggregators also should obtain appropriate profits and be able to adjust part of profits with regard to buildings' performances, which are the basis of sustainable DR market operation. Consequently, an effective bidding method for aggregators needs to be proposed to coordinate both the interests of buildings and aggregators.

To address the above problems, the bidding mechanisms for both buildings and aggregators are proposed in this paper. Firstly, the regulation costs and regulation capacities are established as a piecewise model to depict their variable relationships. The bidding mechanism that regards the maximum costs per regulation capacity as the bidding prices at different intervals is proposed, so as to generate the capacity-price curves of buildings with the guarantee of regulation profits. Furthermore, the bidding mechanism for aggregators is proposed to formulate the capacity-price profiles, by simplifying the stepwise capacity-price curves of buildings into the maximum bidding price. Besides, the variable coefficient is implemented to allocate the regulation surplus in accordance with regulation performance between buildings and aggregators.

The following sections are organized as follows: Section II introduces the scheme of the DR market and the generating mechanism of the capacity-cost as well as the capacity-price curves at buildings level. Section III illustrates the aggregation method of buildings and the relevant clearing rules, followed by the profits allocation method based on the variable coefficient. The case study is conducted in Section IV. Section V summarizes the remarks of this paper.

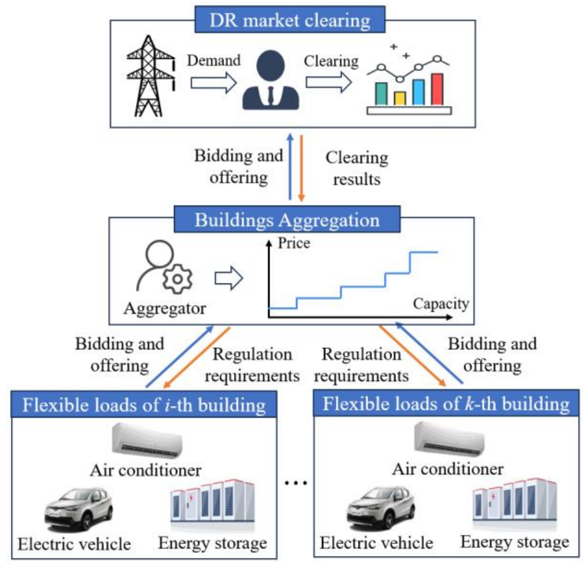

Fig. 1 The scheme of DR market and relevant bidding processes

II. THE GENERATING MECHANISM OF CAPACITY-PRICE CURVE OF BUILDINGS

In this section, the participants composition and structure of the DR market are introduced first to illustrate the bidding process of the DR market. Then, the capacity-cost of the building is developed to depict the regulation costs variations with the regulation capacity. Finally, the bidding strategy of the building is proposed to guarantee the regulation profits.

A. The participants and biding process of the DR market

The participants of the DR market are mainly composed of the system operator, the aggregators, and the users of buildings, as shown in Fig. 1. Firstly, the users of buildings need to submit their capacity-price curves to the affiliated aggregator, which are formed based on the actual regulation costs as well as the regulation capacity of flexible loads. After collecting information from buildings, the aggregator will formulate the capacity-price profiles including all buildings and send them to the system operator. Then, the system operator finishes the market clearing according to the regulation demands of power systems. Lastly, the clearing results are sent to corresponding buildings from the market operator layer by layer.

B. The costs-capacities curves of buildings

There are various flexible loads in buildings, which possess different regulation features and costs. Even for the same flexible load, the regulation costs are related to the regulation capacities. Specifically, with respect to TCLs, the regulation capacities of a 2 ℃ temperature increase are approximately twice that of a 1 ℃ increase. However, the associated regulation costs of 2 ℃ are significantly higher than twice than those of a 1 ℃ increase, due to the exacerbated thermal discomforts caused by the higher temperature.

To reveal the relationship between regulation capacities and regulation costs, the appropriate capacity-cost model should be developed before generating the bidding profiles. Without loss of generality, several assumptions are established as follows:

1) Take the scenario of load-shedding as an example to illustrate the bidding mechanism in the following sections.

2) The capacity-cost curve of the building consists of 3 consecutive lines with different slopes.

3) The regulation costs increase linearly with the regulation capacities at different stages.

It should be noted that the above assumptions are not compulsory but for simplifying the problem. For clarity, the load-shedding and the valley-filling are dual problems, it's easy to transform the load-shedding to valley-filling situations. Then, the whole capacity-cost curve can be divided into fewer or more segments according to practical demands. Lastly, the relationship between regulation costs and regulation capacity is not limited to linear increase, other types of growing trends are also suitable.

As mentioned above, the relationship between costs and capacities is modeled linearly with 3 stages, as shown in Fig. 2 (a). Denoting ΔP_i as the regulation capacity of the i-th building, the regulation costs $c_i(\Delta P_i)$ per regulation capacity can be expressed as follows:

$$c_i(\Delta P_i)=\begin{cases} m_{i,1}\Delta P_i+n_{i,1} & 0<\Delta P_i\le \Delta P_{i,1}^{\max} \\ m_{i,2}(\Delta P-\Delta P_{i,1}^{\max})+n_{i,2} & \Delta P_{i,1}^{\max}<\Delta P_i\le \Delta P_{i,2}^{\max} \\ m_{i,3}(\Delta P-\Delta P_{i,2}^{\max})+n_{i,3} & \Delta P_{i,2}^{\max}<\Delta P_i\le \Delta P_{i,3}^{\max} \end{cases} \quad (1)$$

where

$$m_{i,1}<m_{i,2}<m_{i,3} \quad (2)$$

$$n_{i,2}=m_{i,1}\Delta P_{i,1}^{\max}+n_{i,1} \quad (3)$$

$$n_{i,3}=m_{i,2}\Delta P_{i,2}^{\max}+n_{i,2} \quad (4)$$

where $m_{i,1}$, $m_{i,2}$, and $m_{i,3}$ represent the slopes of 3 lines, respectively. $n_{i,1}$, $n_{i,2}$ and $n_{i,3}$ mirror the constant values, respectively. $\Delta P_{i,1}^{\max}$, $\Delta P_{i,2}^{\max}$, and $\Delta P_{i,3}^{\max}$ are the cumulated maximum regulation capacity of 3 stages, respectively.

As shown in Fig. 2, the capacity-cost lines at different stages are connected end to end. Therefore, the cumulated regulation costs are the integration of $c_i(\Delta P_i)$, which can be calculated as follows:

$$Cost(\Delta P_i)=\int_0^{\Delta P_i} c_i(\Delta P_i)d(\Delta P_i) \quad (5)$$

where $Cost(\Delta P_i)$ is the cumulated costs with ΔP_i regulation capacity.

C. Generating Mechanism of the capacity-price curve

After formulating the capacity-cost curves, the building needs to submit its capacity-price profiles to the aggregator. To guarantee the profits of regulation, the regulation income should be higher than regulation costs, which is calculated by equation (5) and represented by the orange shadow area in Fig. 2 (b). It should be noted that the regulation costs have covered the compensation for users, such as the thermal discomforts, waiting time, and so on. As a result, the profits mean extra incentives to encourage buildings to be involved in the DR program.

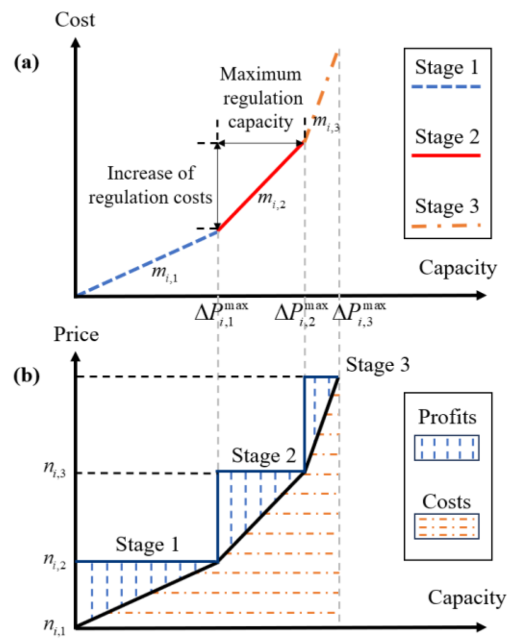

Fig. 2 The illustration of bidding process: (a) the capacity-cost curve. (b) the capacity-price curve.

With regard to market rules, the capacity-price curve should be stepwise. In order to satisfy the requirements on both profits and market rules at the same time, hence, the maximum costs per regulation capacity at different stages are chosen as the bidding prices, respectively. As shown in Fig. 2, the stepwise blue line represents the capacity-price curve, and the areas with blue shadow indicate the extra profits of the DR regulation.

Finally, the i-th building needs to submit corresponding parameters to the aggregator, which can be expressed using the following array:

$$\begin{Bmatrix} [n_{i,1}, m_{i,1}, \Delta P_{i,1}^{\max}] \\ [n_{i,2}, m_{i,2}, \Delta P_{i,2}^{\max}] \\ [n_{i,3}, m_{i,3}, \Delta P_{i,3}^{\max}] \end{Bmatrix} \quad (6)$$

III. The Bidding Mechanism of Aggregators and Profits Allocation Method

In this section, the bidding mechanism is proposed firstly to generate the capacity-price profiles, which can guarantee the profits of aggregators and practical soundness at the same time. Then, the clearing rules of the DR market are introduced, followed by the profits allocation method utilizing the variable coefficient.

A. The aggregation method of different buildings

After obtaining all capacity-price curves provided by buildings, the aggregator should generate the final capacity-price profiles. Considering every building has 3 groups of

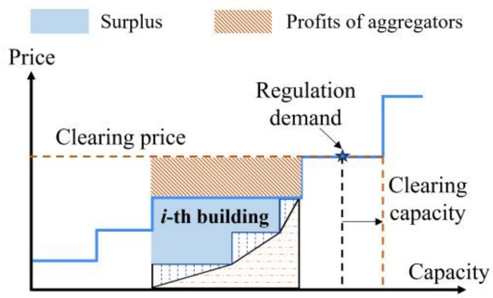

Fig. 4 The market clearing mechanism and the profits allocation

regulation capacities and regulation costs, it's impossible to order them sequentially and formulate the complex capacity-price profiles with too many intervals. Furthermore, this aggregation method will lead to the situation that almost every building is allocated some regulation capacities, which will introduce much more regulation pressure to buildings.

Consequently, the capacity-price curve of the building is simplified into a group of capacity and price and represented by the tuple $[Cap_i, Price_i]$:

$$Cap_i = \Delta P_{i,3}^{\max} \tag{7}$$

$$Price_i = m_{i,3}(\Delta P_{i,3}^{\max} - \Delta P_{i,2}^{\max}) + n_{i,3} \tag{8}$$

Besides, all buildings will be sorted by the $Price_i$ from lowest to highest, hence, the $Price_i$ satisfies the following constraints:

$$Price_j \le Price_i \le Price_k, \forall j < i, \forall k > i \tag{9}$$

Finally, assuming there are N buildings aggregated by the aggregator, the aggregated stepwise capacity-price profiles are formulated, which can be expressed as a set of tuples:

$$\{[Cap_1, Price_1], ..., [Cap_i, Price_i] ..., [Cap_N, Price_N]\} \tag{10}$$

B. Market clearing rules and profits allocation method

After the capacity-price profiles are submitted to the DR market operator, the operator will finish the DR market clearing with regard to the regulation capacity. Referring to the rules of the DR market in Guangdong province, the maker clearing mainly obeys the following rules [9].

1) All market participants are sorted by bidding price from low to high, the clearing principle is meeting the demand of regulation capacity.

2) When the bidding prices are the same, they will be ordered with regard to the submitting time. If the two are completely the same, they will be sorted by the capacity from large to small.

3) For the marginal units, the bidding capacity will be cleared totally.

4) The marginal clearing pricing model is adopted, and the clearing price is the bidding price of the marginal unit.

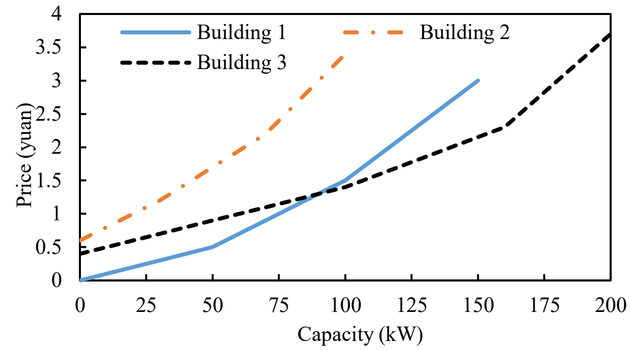

Fig. 3 The cost-price curves of buildings

As shown in Fig. 3, the 4th building is chosen as the marginal unit according to the regulation demand. As a result, the clearing price is equal to the bidding price of the 4th building. Due to the full capacity clearing rule, the capacity of the 4th building will be cleared totally, thereby the final clearing capacity is the sum of the capacity of the first 4 buildings, which is a little larger than the demand of regulation capacity.

Assuming the clearing price is p_c, in terms of i-th building, the capacity-price profiles submitted by the aggregator are $[Cap_i, Price_i]$, respectively.

Therefore, the fixed profits of aggregators in the i-th building $Income_{i,f}^a$ can be expressed as follows, which is represented by the orange shadow area in Fig. 3:

$$Income_{i,f}^a = (p_c - Price_i)Cap_i \tag{11}$$

For the i-th building, the fixed profits can be calculated based on its submitted capacity-price once it wins the bidding, so the $Income_{i,f}^b$ can be expressed as:

$$\begin{aligned} Income_{i,f}^b &= \Delta P_{i,1}^{\max}(m_{i,1}\Delta P_{i,1}^{\max} + n_{i,1}) \\ &+ [m_{i,2}(\Delta P_{i,2}^{\max} - \Delta P_{i,1}^{\max}) + n_{i,2}](\Delta P_{i,2}^{\max} - \Delta P_{i,1}^{\max}) \\ &+ [m_{i,3}(\Delta P_{i,3}^{\max} - \Delta P_{i,2}^{\max}) + n_{i,3}](\Delta P_{i,3}^{\max} - \Delta P_{i,2}^{\max}) \end{aligned} \tag{12}$$

Besides, there are extra profits named surplus as shown in the blue area, which is generated by the higher bidding price of aggregators.

$$Surplus_i = Cap_i \cdot Price_i - Income_{i,f}^b \tag{13}$$

To encourage buildings to actively provide regulation capacity with better performance, part of the surplus will be delivered to the building with a variable coefficient λ_i. The determination of λ_i can be decided according to the participation times, finishing rate, and so on. Therefore, the variable incomes of buildings and aggregators can be calculated as follows:

$$Income_{i,v}^b = \lambda_i \cdot Surplus_i \tag{14}$$

$$Income_{i,v}^{a} = (1-\lambda_i)Surplus_i \quad (15)$$

where $Income_{i,v}^{b}$ and $Income_{i,v}^{a}$ represent the variable incomes of the building and the aggregator of the i-th building, respectively.

IV. Case Study

To prove the effectiveness of the proposed bidding mechanism and profits allocation method, the case study is conducted in this section.

A. Parameters setting

In the case study, 3 buildings under an aggregator are set to participate in the DR market, although the participants are relatively less, it will not affect the results illustration of the proposed mechanism. The price ceiling is set as 4 yuan per kW with regard to rules in many provinces in China. To represent the regulation features of different types of buildings, their regulation costs and regulation capacities are set with significant differences. The detailed cost-price curves of 3 buildings are shown in TABLE I.

TABLE I The cost-price parameters of buildings

Bidding information		Building number		
		Building 1	***Building 2***	***Building 3***
Starting price (yuan/kW)		0	0.6	0.4
Stage 1	Price slope (yuan/kW)	0.01	0.02	0.01
	Capacity (kW)	50	30	100
Stage 2	Price slope (yuan/kW)	0.02	0.025	0.015
	Capacity (kW)	50	40	60
Stage 3	Price slope (yuan/kW)	0.03	0.04	0.035
	Capacity (kW)	50	30	40
Total capacity (kW)		150	100	200
Maximum Price (yuan/kW)		3	3.4	3.7

B. Results analysis

The cost-price curves of 3 buildings are shown in Fig. 4, where the blue solid line, the orange dot-dash line, and the black dotted line represent building 1, building 2, and building 3, respectively. Compared with building 2 and building 3, the starting price of building 1 is zero. Besides, building 1 has the lowest bidding price, which is beneficial for increasing the possibility of the win of bidding, especially when the demand for regulation capacity is not high. Building 3 possesses the maximum regulation capacity, which is an advantage when there are more than 2 buildings providing the same price.

According to the proposed bidding mechanism, the capacity-cost curves and capacity-price curves of buildings as well as the aggregator are shown in Fig. 5, respectively. It can be seen that the buildings are sorted by the maximum bidding price, in which building 1 is 3 yuan, building 2 is 3.4 yuan, and building 3 is 3.7 yuan. Obviously, the fixed profits of aggregators are affected by the maximum bidding price and the regulation capacity. Therefore, to earn more profits, the aggregator is encouraged to find and manage more promising resources with high regulation capacity and low regulation costs, which are also the proactive effects of introducing the DR market.

Assuming all buildings win the biddings and the clearing price is 4 yuan, the specific arrangement of profits is analyzed in the following content. As shown in Fig. 6, the blue cylinders, the pyramids, and the purple cuboids mirror the aggregator profits, buildings profits, and the surpluses, respectively. It can be seen that the aggregator's profits per regulation capacity decline with the bidding price, e.g., the profits of both building 2 and building 3 are 60 yuan, though the regulation capacity of buildings is twice as many as that of building 2. On the contrary, the building's profits of per regulation capacity are increasing with the bidding price, which are 1.67 yuan/kW, 2.26 yuan/kW, and 2.13 yuan/kW, respectively. Different from the former 2 elements, the surpluses appear a specific variation trend, due to the profits depending on both regulation capacity and bidding price.

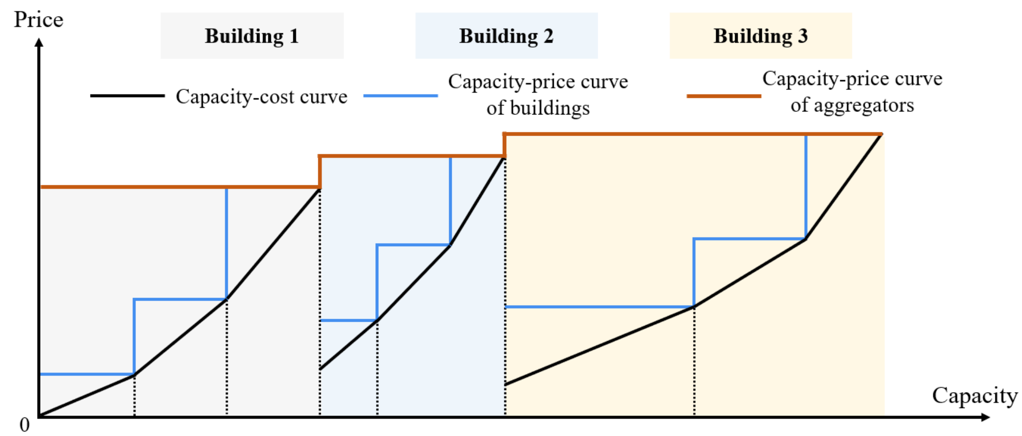

Fig. 5 The illustration of bidding process from buildings to aggregators

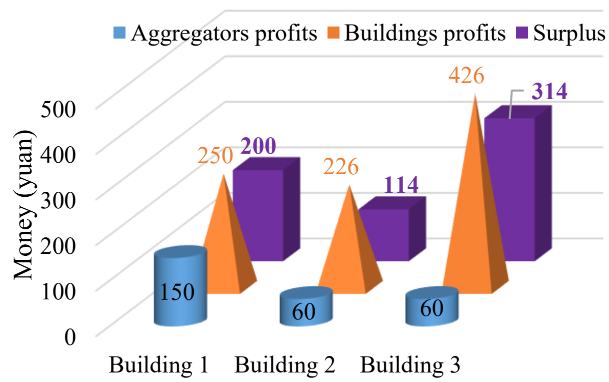

Fig. 6 The profits allocation of buildings and aggregators

TABLE II The total income of buildings and aggregators with different allocation coefficients

Participants	Allocation coefficients		
	$\lambda = 0.25$	$\lambda = 0.5$	$\lambda = 0.75$
Building 1/yuan	300	350	400
Aggregator/yuan	300	250	200
Building 2/yuan	254.5	283	311.5
Aggregator/yuan	145.5	117	88.5
Building 3/yuan	504.5	583	661.5
Aggregator/yuan	295.5	217	113.5

Apart from the fixed profits, the allocation of surplus is also of great importance. To analyze the effects caused by allocation coefficients on total incomes, different coefficients are chosen to calculate the total incomes of buildings and aggregators, which are shown in TABLE II. Because the surplus accounts for a significant proportion of total profits, the intuitive knowledge is that a larger coefficient will increase the income of buildings while decrease that of aggregators. In fact, the coefficient can play an important role between the buildings and aggregators. For instance, the coefficient can be related to the regulation performance, the buildings are motivated to update their devices and provide better response performance, so as to obtain more profits by getting a higher coefficient. Meanwhile, the aggregator can also receive more returns from the DR market, obviously, it is a win-win method for both buildings and aggregators.

V. Conclusion

To accommodate the increasing RESs, buildings are exploited to provide regulation capacity under electricity markets. Considering the regulation costs of buildings vary with regulation capacity, an efficient bidding mechanism is proposed to coordinate the interests of different participants. By establishing the piecewise model on regulation costs and regulation capacities, the bidding mechanism for buildings is proposed to generate the capacity-price profiles. Then, the bidding mechanism for aggregators is proposed to formulate the capacity-price profiles through regarding a building as an entirety, and the maximum price is chosen as the bidding price. Not only the aggregation complexity with lots of parameters is simplified effectively, but also can guarantee profits for aggregators. Moreover, the variable coefficient method is also proposed to allocate the surplus with regard to buildings' regulation performance. Finally, the effectiveness of the proposed mechanism is proved by the case study.

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