Equilibrium Analysis on the Main Energy and Ancillary Service Joint Market Considering Load Aggregators

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Abstract. In-depth mining of the adjustment capacity and value of demand-side load resources under the background of marketization is an important support for realizing the safe operation of the power grid and efficient operation of the power market in the future. This paper takes the load aggregator as the object, exploring its market operation ability through the main energy and ancillary service joint market simulation analysis. Firstly, the transaction framework of main energy market and frequency modulation ancillary service joint market considering load aggregators is built, then the market participation mode and the cost of each entity are analyzed. Secondly, based on the game equilibrium theory of oligopoly competition, a load aggregators included multi-period equilibrium model of energy and frequency modulation ancillary service joint market is established. Finally, the nonlinear complementarity method is applied to solve the model, and the rationality and effectiveness of the proposed model are verified through typical case analysis. The results show that with the participation of load aggregators, the effect of "peak shaving and valley filling" on both load and active power price is obvious, up and down frequency regulation capacity prices of the system have decreased, and the downward adjustment is more prominent, the purchase cost is reduced, and the user profit and social welfare can increase. It provides reference for future market planning as well as EVA operation.

1.Introduction

With the deterioration of environmental problems and development of demand side response technology, a large proportion of demand side load resources will join the market for trading in the future. Participation of large-scale small and medium-sized loads will pose greater challenges to the operation of power grid. The load aggregator (LA) can control the load side resources including small and medium-sized user resources, energy storage resources and electric vehicles, as well as participate in the spot market competition. Through certain strategies, LA can not only suppress or eliminate the adverse impact of uncertain load on power grid, but also provide ancillary services such as frequency modulation (FM) and peak shaving, etc. As an operator, LA mainly have two strategies in the spot market bidding. One is the electricity demand and quotation of each type per period. Different market strategies will affect the market clearing price and its own income; on the other hand, after the demand and price are determined, the adjustable capacity of various loads will also be pinned. How to utilize this part of capacity in the ancillary service market will determine another part of the revenue of LA [5].

As a new market entity, LA’s participation impact on the clearing results of the main and ancillary markets and the profits of all market entities is worth further study.

In this premise, based on the game equilibrium theory of oligarch competition, this paper studies the equilibrium results of load aggregators participating in the main energy and ancillary service joint markets at the same time. Firstly, the trading framework of the joint market is established, then the
cost of each entity participating in the frequency modulation market is analyzed. Secondly, multi-
period equilibrium model of energy and frequency modulation market considering LA is established.
The influence on the clearing results and the profits of all parties with and without LA is compared
through simulation. Quantitative sensitivity analysis of adjustable load properties is also carried out.

2. Market Transaction Rules and Entity Cost Analysis

2.1. Market Trading Framework
Assuming that there are two parts of the day ahead spot market in a certain initial stage, the main
energy market and the frequency modulation ancillary service market. There are n traditional
generation companies and 1 LA in the market. Each entity participates by Cournot competition.
According to its own strategy, the competitive capacity in the main and ancillary markets are reported
respectively. The two parts of capacity reported shall meet the basic physical constraints. The trading
center will test the reported capacity and clear the both markets.

After receiving the up (down) order in working period, the bid winning entity in FM ancillary
service market will increase (reduce) the unit output of the traditional generator providing up (down)
capacity, and the LA shall control the load resources to increase or decrease.

In this paper, the mileage income is not considered in the settlement, and the energy exchange due
to participating in FM is settled according to the energy market price in the bidding period. And we
adopt the independent clearing mode

2.2. Transaction Cost Model of Market Entity
The cost of traditional power generator \(i\) (\(i=1,2,\ldots,n\)) in \(t\) period can be described as a quadratic
function of output:

\[
C_{i,t}^{e} = 0.5a_i P_{i,t}^2 + b_i P_{i,t}
\]

Where: \(P_{i,t}\) is the active power output of the generation company \(i\) in time period \(t\); \(a_i, b_i\) are the cost
coefficients of traditional generators.

Without considering the investment cost, the ancillary cost brought by the participation of power
generation companies in the FM ancillary service market can also be fitted as a quadratic function of
the FM capacity:

\[
C_{i,t}^{a} = 0.5a_i^{up} Q_{i,t}^{up2} + b_i^{up} Q_{i,t}^{up} + 0.5a_i^{down} Q_{i,t}^{down2} + b_i^{down} Q_{i,t}^{down}
\]

Where: \(Q_{i,t}^{up}, Q_{i,t}^{down}\) is the up and down FM capacity of the traditional power producer \(i\); \(a_i^{up}, b_i^{up}, a_i^{down},
\(b_i^{down}\) are the up and down FM cost coefficient of the traditional generator \(i\).

In FM ancillary service market, the cost of LA’s FM capacity is as follows:

\[
C_{L,A,t}^{\text{up}} = \sigma_i^{up} c Q_{L,A,t}^{up} - \sigma_i^{up} \lambda_i Q_{L,A,t}^{up}
\]

\[
C_{L,A,t}^{\text{down}} = \lambda_i \sigma_i^{down} Q_{L,A,t}^{down}
\]

In formula (3), the first and second terms are the loss and electricity settlement cost when the
capacity is increased, formula (4) is the electricity settlement cost caused by capacity reduction; \(\sigma_i^{e}\)
and \(\sigma_i^{a}\) are the up and down FM rates in time period \(t\); \(c\) is the aging cost mobilizing the resources.

In the main energy market, LAs have to purchase electricity to meet the next day’s load demand. At
the same time, they can store the energy at valley load time (in low price) or discharge at peak load
period (in high price). While completing the arbitrage of charging and discharging, it can cut the peak
and fill the valley for the system load. The output of LA can be expressed as:

\[
P_{L,A,t} = P_{L,A,t}^{\text{out}} - P_{L,A,t}^{\text{in}} - L_i
\]
3. Equilibrium Model of Main and Ancillary Market Considering LAs

3.1. Market Clearing Rules
Dividing a day into 24 time periods, the power demand function of period $i$ is:

$$D_i = \alpha - \beta \lambda_i$$  \hspace{1cm} (6)

Where: $D_i$ is the power demand of time period $i$; $\alpha$, $\beta$ are constants greater than zero; $\lambda_i$ is the power price of time period $i$. The clearing rules of main energy market in $i$ period are shown in formula (7).

$$\sum_{i=1}^{n} P_{i,j} + P_{up}^{out} - P_{down}^{in} - L_i = \alpha - \beta \lambda_i$$  \hspace{1cm} (7)

The specific clearing rules are as follows:

$$\min \sum_{i=1}^{n} (Q_{up}^{i} P_{up}^{i} + Q_{down}^{i} P_{down}^{i}) + Q_{up}^{LA} P_{up}^{LA} + Q_{down}^{LA} P_{down}^{LA}$$  \hspace{1cm} (8)

s.t.  
$$\sum_{i=1}^{n} (Q_{up}^{i} + Q_{down}^{i}) = \delta D_i \cdot \lambda_{up}^{i}$$  \hspace{1cm} (9)

$$\sum_{i=1}^{n} (Q_{down}^{i} + Q_{down}^{i}) = \delta D_i \cdot \lambda_{down}^{i}$$  \hspace{1cm} (10)

$$0 \leq Q_{up}^{i} \leq P_{max}^{i} - P_{i,j}$$  \hspace{1cm} (11)

$$0 \leq Q_{down}^{i} \leq P_{min}^{i} - P_{i,j}$$  \hspace{1cm} (12)

$$0 \leq Q_{up}^{LA} \leq (P_{up}^{LA} - P_{down}^{LA} - L_i)$$  \hspace{1cm} (13)

$$0 \leq Q_{down}^{LA} \leq (P_{up}^{LA} - P_{down}^{LA} - L_i)$$  \hspace{1cm} (14)

Where: $Q_{up}^{i}$, $Q_{down}^{i}$ are the up and down FM capacity of LA respectively; $P_{up}^{i}$, $P_{down}^{i}$ are the up and down FM capacity strategy prices of traditional generator $i$ and LA respectively; $P_{max}^{i}$, $P_{min}^{i}$ are the up and down output limits of generation company $i$; $P_{max}^{LA}$ is the maximum charging and discharging power of the LA; and $\delta$ is the proportion coefficient of the FM demanded capacity in load. The Lagrange multipliers $\lambda_{up}^{i}$, $\lambda_{down}^{i}$ are the clearing prices of up and down FM capacity respectively.

3.2. Decision Making Model of Market Entity
The decision model of traditional power producer $i$ ($i=1,2,\ldots,n$) can be expressed as:

$$\max \sum_{i=1}^{n} \left( \lambda_{i} (P_{i,j} + \sigma_{i} Q_{up}^{i} - \sigma_{i} Q_{down}^{i}) + A_{i} (Q_{up}^{i} \lambda_{up}^{i} + Q_{down}^{i} \lambda_{down}^{i}) - C_{up}^{i} - C_{down}^{i} \right)$$  \hspace{1cm} (15)

Constraints include formulas (7)–(14), as well as climbing constraints. Where, $A_i$ is the FM performance index of generator $i$.

The decision model of LA is:

$$\max \sum_{i=1}^{n} \left[ \lambda_{i} (P_{up}^{LA} - P_{down}^{LA} - L_i) - cP_{up}^{LA} + A_{i} (Q_{up}^{LA} \lambda_{up}^{i} + Q_{down}^{LA} \lambda_{down}^{i}) - C_{up}^{LA} - C_{down}^{LA} \right]$$  \hspace{1cm} (16)

s.t.  
$$\sum_{i=1}^{n} L_i = L$$  \hspace{1cm} (17)

$$0 \leq \sum_{i=1}^{n} \left[ \eta(P_{up}^{LA} + \sigma_{i} Q_{up}^{LA}) - (P_{up}^{LA} + \sigma_{i} Q_{up}^{LA}) / \eta \right] \leq S$$  \hspace{1cm} (18)

Where: $A_{LA}$ is the FM performance index of LA. Equation (17) indicates that the total charge in one day shall meet the demand in the next day. Equation (18) indicates that the charge and discharge capacity used for arbitrage and ancillary services should always be kept within the effective capacity.
of the load resources; where: \( \eta \) is the charge discharge conversion coefficient and \( S_{\text{eff}} \) is the effective capacity of the load resources. Nonlinear complementary method is used to solve the model.

4. Example Analysis
Considering that there are two traditional generation companies (G1, G2) and one LA in day ahead spot market, both participate in main energy market and FM ancillary market at the same time. The parameters of traditional generators are shown in Tab.1. It is assumed that demand is about one tenth of the total load after the decomposition of medium and long-term electricity in a certain day. In linear demand function \( D_t = \alpha_t - \beta_t \lambda_t \) of energy market, the constant value \( \alpha_t \) in each period is 0.6MW/USD, as shown in Tab.2. The next day’s total load demand \( L_d \) is 20MW•h, The effective load resources capacity \( S_{\text{eff}} \) is 80MW•h, the charge and discharge limit of each period is 20MW, the charge-discharge conversion coefficient \( \eta \) is 0.85, and the aging cost coefficient \( c \) of unit discharge battery is 60USD/(MW•h).

The proportion coefficient \( \delta \) of the of the up and down FM capacity demand to the load is 4\%, and the call rate of the up and down FM capacity \( \sigma_{\text{up}}^t, \sigma_{\text{down}}^t (t=1,2,\ldots,n) \) are 0.2. The FM performance indexes of G1, G2 and LA are all 1.

| Parameters | G1 | G2 |
|------------|----|----|
| \( P_{\text{max}}^i \)/MW | 60 | 80 |
| \( P_{\text{min}}^i \)/MW | 10 | 15 |
| \( v_i \)/MW | 12 | 12 |
| \( \alpha_i \)/(USD/MW•h) | 1.2 | 1.0 |
| \( \beta_i \)/(USD/MW^2•h) | 10 | 10 |
| \( a_{\text{up}}^i \)/(USD/MW•h) | 0.96 | 0.8 |
| \( b_{\text{up}}^i \)/(USD/MW^2•h) | 8 | 8 |
| \( a_{\text{down}}^i \)/(USD/MW•h) | 0.96 | 0.8 |
| \( b_{\text{down}}^i \)/(USD/MW^2•h) | 8 | 8 |

| Time | 1 | 2 | 3 | 4 | 5 | 6 |
|------|---|---|---|---|---|---|
| \( \alpha_t \)/MW | 82 | 72 | 70 | 66 | 72 | 82 |
| Time | 7 | 8 | 9 | 10 | 11 | 12 |
| \( \alpha_t \)/MW | 122 | 158 | 188 | 198 | 218 | 228 |
| Time | 13 | 14 | 15 | 16 | 17 | 18 |
| \( \alpha_t \)/MW | 248 | 252 | 248 | 244 | 238 | 234 |
| Time | 19 | 20 | 21 | 22 | 23 | 24 |
| \( \alpha_t \)/MW | 238 | 242 | 228 | 198 | 148 | 108 |

4.1. Equilibrium price of main energy market and FM ancillary market in different conditions
Fig.1 shows the equilibrium price of main energy market with and without LAs. It is clear that: the change trend of equilibrium price is consistent with that of load; the participation of LAs has the effect of peak shaving and valley filling, which is due to the increase of load by LA during night charging and the increase of power supply during daytime discharge.
Fig. 2 shows the equilibrium price of FM ancillary market with and without LAs. Firstly, due to the same cost parameters of up and down FM of traditional generators, when no LA is participating, the clearing price of up and down FM capacity is the same; when LA participates, the price decreases in each period, which is because LA reduces the traditional generators’ participation in FM ancillary market. Due to the impact of electricity settlement on FM market cost, LAs have lower cost when capacity increase, stronger competitiveness and more obvious reduction effect on market price. Therefore, the increase capacity price is lower than reduction price.

4.2. Bid Winning Capacity of Each Market Entity
Fig. 3 shows the bid winning active power output of traditional generators and LAs. In terms of active power output, LAs charge at night and discharge in daytime, compared to disorderly charging, it has the effect of peak shaving and valley filling on the total load.
Fig. 4 shows the up FM capacity for each entity. At night, the up capacity and the rising speed of bidding capacity of LAs are higher than that of traditional generators, since the settlement of electricity brought by capacity increase reduces the cost of LAs, while traditional generators have greater loss of thermal efficiency and lower competitiveness with the increase of capacity. In the peak load stage, due to the physical constraints of LA arbitrage discharge, the capacity provided by traditional generators is limited, so their bid winning capacity increases significantly.

Fig. 5 shows the down FM capacity of each market entity. Due to high cost of down FM capacity caused by electricity settlement, the competitiveness of LAs is not as good as that in up FM capacity market. At night, with arbitrage charging, LAs reduce the capacity to meet the maximum of physical constraints. In the daytime, due to the lack of competitiveness of LAs, the bidding capacity is less than that of traditional generators.

5. Conclusion
Based on the game equilibrium theory of oligopoly competition, this paper establishes a multi-period equilibrium model of main and FM ancillary market with the participation of LAs. Through example analysis, the impact of LAs’ participation on the equilibrium results of spot market is comparatively studied

1) The arbitrage charging and discharging behavior of LAs with "low charging and high discharging" has the effect of peak shaving and valley filling. Meanwhile, the electricity price will rise in the low period and decrease in the peak period.

2) LAs use the remaining capacity to participate in FM ancillary market, reducing the price of both the up and down FM capacity. Since the cost of increasing capacity is lower than the cost of reducing, the bidding capacity of LAs is higher than that of decreasing, which has more obvious effect on reducing the price of system capacity.

3) The participation of LAs in the spot market will effectively weaken the power of other market entities, reduce the profits of traditional generators and the purchase cost of FM services. Users’ profits will decrease in the low period and increase in the peak period, and the whole day profits and social welfare will increase.

4) The increase of adjustable load capacity will promote the further growth of social welfare, but the growth trend will gradually slow down and eventually be stable.

Acknowledgments
This work was sponsored by the State Grid Sichuan Economic Research Institute Project (Research on transaction mode and strategy of electricity spot market for newly-emerging resource entities).

References
[1] Zhang W, Wu B, Li W, et al. Discussion on development trend of battery electric vehicles in China and its energy supply mode[J]. Power System Technology, 2009, 33(4): 1-5.
[2] Wen G, Weng W, Zhao Y, Jiang C. Source-load interaction two-layer optimization model considering the participation of load aggregators[J]. Power System Technology, 2017, 41(12): 3956-3963.
[3] Wang X, Xie M, Zhang S. Analysis on equilibrium of electricity market under grid-integration of electric vehicles[J]. Power System Technology, 2014, 38(11): 2993-2998.
[4] Chen Z, Jing Z, Chen D, et al. Analysis on Pricing Mechanism in Frequency Regulation Ancillary Service Market of United States[J]. Automation of Electric Power Systems, 2018, 42(12): 1-10.
[5] Yang G. Study on the joint optimization decision of main market and auxiliary service market of electric energy [D]. Shanghai Jiaotong University, 2011.
[6] Wang X, Wang L, Zhang S. Impacts of cooperation between wind power producer and DR aggregator on electricity market equilibrium [J]. Power System Technology, 2018, 42(1): 110-116.