Game analysis of decreasing generation cost characteristics in electricity spot market

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Abstract. The construction of Chinese electricity spot market is in its infancy. Market rules have borrowed from foreign mature market experiences, adopted marginal electricity price settlement mechanisms, and stipulated that the biddings on the power generation side will increase monotonously. However, there are thermal power generating units in China whose marginal cost does not meet the characteristics of monotonous increase. In this context, studying the strategic behaviour of thermal power generating units with diminishing marginal cost characteristics in the market, highlighting the impact of existing rules on market participants’ decision making, is of great significance to the design and operation of Chinese electricity spot market. First, an existing generation market clearing model based on monotonically increasing quotes and a strategy model for generating units based on monotonically decreasing marginal costs are established. Then, the above models are organically combined to form a bilevel optimization model, and the iterative optimization is performed to obtain a market equilibrium solution. Finally, a numerical example is used to clearly describe the bidding strategy of the unit in the spot market, and the incentive effects of market regulations on its bidding behaviour are discussed.

1. Introduction
Many mature power spot markets in the world use marginal electricity price settlement mechanisms, and require the generation to submit monotonically increasing segmented ladder quotes [1-2], which helps to quickly realize the clearing operation of market transactions and realize electricity Real-time settlement [3-4]. Moreover, according to the marginal electricity price theory, the optimal bidding strategy of the power generation company is based on the marginal cost as the basis for bidding, and the bidding equilibrium results obtained by it can achieve the optimal of individual and overall interests [5]. But the derivation of the above conclusions is based on the specific assumption that the unit in the market has a monotonically increasing marginal cost characteristic.

However, in practice there are thermal power generating units, especially the large-scale coal units in China, and their marginal cost shows a decreasing trend in a wider output range [6-7], which is contrary to the market bidding regulations. Monotonically decreasing marginal cost curves are difficult to fit effectively through monotonically increasing ladder quotes. In a separate electricity spot market, the actual generating cost of the unit may be severely distorted by the bidding, and the individual interests of the unit and the overall interest incentives of the market are likely to be incompatible [8-9].

At this time, power units can no longer simply use marginal cost as the basis for bidding, but need to study their own overall power generation cost characteristics to formulate bidding strategies.
Literature [10] used conventional thermal economic analysis methods to study the cost characteristics of units, and established SPF model to study the corporate competition strategy of multiplayer non-cooperative games. Reference [11] fitted the coal consumption curve for the typical coal-fired unit cost changes, and designed a bidding strategy based on the trading mechanism of the electricity spot market.

In addition to its own cost analysis, power generation companies need to consider the overall market factors when participating in spot market decisions, adjust their own bidding strategy based on market information, and participate in market competition games. Reference [12] has refined the key factors that influence the bidding on the power generation side, and established a multi-input decision factor model that can simulate the bidding behavior of power units in the market. References [13-15] construct different target benefit functions, and use the Q-learning algorithm to construct a bidding strategy model for power units in the multi-agent bidding environment for the current power market. Reference [16] introduced evolutionary game theory into the bidding strategy of power generation companies, and studied how the power generation side gradually seeks the optimal strategy in an uncertain market environment. Salehizadeh et al. [17] propose a leader–follower game on transmission congestion management (TCM) in power systems. Salehizadeh et al [18] provide a fuzzy Q-learning approach of modeling electricity market in a continuous range of renewable resources’ penetration. Kiannejad et al [19] reveal the behavior of market players by simplifying the market participants model, which can overcome the information uncertainty regards the competitors’ behavior, and propose an optimal bidding strategy with high efficiency.

However, the above literatures all simplify the assumption of monotonically increasing the marginal cost of power generation, and do not consider the monotonically decreasing characteristics of the cost of generating units in practice. Based on the above background, the existing spot market clearance model based on monotonically increasing bidding and the genset strategy model based on monotonically decreasing marginal cost are established. Then, the above models are organically combined to form a bilevel optimization model, and iterative optimization seeks to obtain a market equilibrium solution. Finally, a numerical example is used to describe the market bidding strategy of units in the spot market, and the incentive effect of market regulations on their bidding behavior is analyzed.

2. Clearing model of electricity spot market

2.1. Objective function

In general, the objective function of the spot market in the electricity market is to maximize social welfare, that is, to maximize the demand-side surplus and the power-generation surplus. When all load demand is assumed to be fixed, the basic objective function of the problem is to minimize the generation cost of electricity market, which can be formulated as the following optimal function:

\[ F = \min \sum_{t} \sum_{i} C(p_{it}) \]  

(1)

Where \( F \) is the objective function of the model, \( C(p_{it}) \) is total cost of unit \( i \) in the time \( t \), \( p_{it} \) is the output of unit \( i \) in the time \( t \).

2.2. System real power balance constraints

\[ \lambda_t : \sum_i p_{it} = d_t, t = 1,2, \ldots, T \]  

(2)

Note that \( d_t \) is the market demand in the time \( t \). And the Lagrange multiplier \( \lambda_t \) represents the shadow price of system constraint (2), which also means the marginal price of the power system in the time \( t \).
2.3. Network transmission constrains

\[ \bar{\eta}_i: \sum S_{il} P_l \leq \bar{P}_l, l = 1, 2, ..., L \]  
\[ \eta_i: \sum S_{il} P_l \geq \bar{P}_l, l = 1, 2, ..., L \]  
\[ (3) \] \[ (4) \]
Where \( \bar{P}_l \) and \( P_l \) are the maximum and minimum transmission capacity of system branch \( l \). \( S_{il} \) represents the shift factor of unit \( i \) to the branch \( l \). \( \eta_i \) and \( \bar{\eta}_i \) represents the shadow price of network transmission constraints (3)(4) and \( p_i \) is the output of unit \( i \).

2.4. Locational marginal price

\[ X_{lt} = -\lambda_t + \sum_l S_{il} (\bar{\eta}_l - \eta_l) \]  
\[ (5) \]
Where \( X_{lt} \) contains two components, the first item is the system energy price component, and the second item is the congestion price component.

3. Units strategy model

In order to study closer to the essence of the problem and facilitate a more in-depth discussion and analysis, this paper considers that all units participate in the spot market in a linear bidding function model [20]. The unit’s own cost characteristics are expressed by a monotonically decreasing function.

3.1. Objective function

The bidding strategy of the unit is to maximize its own profit, which is to maximize the difference between its own market revenue and the cost of power generation.

\[ R_i = \max_t \left( X_{lt} \cdot p_{lt} - C(p_l) \right) \]  
\[ (6) \]
Where \( R_i \) represents the profit function of the unit unit, expressed as the market revenue minus the generation cost. \( X_{lt} \) represents the market clearing price of unit \( i \). \( X_{lt} \) and \( p_{lt} \) are derived from the clearance model of the power spot market.

3.2. Units operating constraints

\[ \bar{\varepsilon}_i: p_l \leq \bar{P}_l \]  
\[ \underline{\varepsilon}_i: p_l \geq \underline{P}_l \]  
\[ (7) \] \[ (8) \]
Where \( \bar{P}_l \) and \( \underline{P}_l \) are the maximum and minimum capacity of unit \( i \). \( \bar{\varepsilon}_i \) and \( \underline{\varepsilon}_i \) represents the shadow price of unit operating constraints (7)(8).

3.3. Units cost function

Assuming that the total cost function of the unit is a quadratic function, at this time its marginal cost function is expressed by a linear function.

The total cost function of the unit can be formulated as follows:

\[ TC(p_i) = \frac{1}{2} a_i p_i^2 + b_i p_i + c_i \]  
\[ (9) \]
The marginal cost function of the unit can be formulated as follows:

\[ MC(p_i) = a_i p_i + b_i \]  
\[ (10) \]
Where \( a_i \), \( b_i \) and \( c_i \) are the unit cost parameters.

In the output range of unit \( i \):

\[ P_{\underline{i}} \leq p_i \leq \bar{P}_l \]  
\[ (11) \]
Assuming that \( MC(p_i) \) decreases monotonically as \( p_i \) increases, meaning that parameter \( a_i \) is negative.
3.4 Units bidding function

In order to simplify the calculation and facilitate in-depth analysis of its inherent meaning, the unit's bidding function is expressed as a linear function by 2 parameters. The monotonically increasing bidding function of the unit can be formulated as follows:

\[ S(p_i) = m_i p_i + n_i \]  

(12)

Where \( S(p_i) \) is the bidding function of the unit \( i \). \( m_i \) and \( n_i \) are the bidding parameters. In the output range in eqs.3, \( S(p_i) \) increases monotonically with the increase of unit output \( p_i \), meaning that parameter \( m_i \) is positive.

4. Solution procedure of game model

In the electricity market, when determining the bidding strategy of power units, not only should they consider the bidding strategies of other power units, but also the influence of the demand elasticity curve. These complex influence relations are implicitly included in the optimal (KKT) conditions of the electricity spot market and unit game problems [21]. In order to obtain the Nash equilibrium solution of the joint game problem, we need to obtain the market clearing results and the optimization decision of each power unit according to equations (1)-(4) and (6)-(12).

The game model is formed as a bilevel programming model, the upper optimization model is the clearing model of the power spot market, and the lower optimization model is the unit strategy model. The lower model independently optimizes the bidding parameters of each unit, and the optimized bidding information is fed back to the upper model to clear the spot market. The clearing results of the upper model are re-fed back the lower model for optimization, and the loop recursively iteratively converges to obtain the solution of the overall market game.

Through multiple iterations, when the market game meets equilibrium, the profit function of each unit meets the following conditions, that is, if the unit changes the bidding function, it will not bring increased profits to itself:

\[ \frac{\partial R_i(\mathbf{P})}{\partial m_i} = 0 \]  

(13)

\[ \frac{\partial R_i(\mathbf{P})}{\partial n_i} = 0 \]  

(14)

Where \( R_i \) represents the profit function of the unit \( i \), which is related to the bidding and system load of each member in the market.

The set of unit bidding parameters \( m_i \) and \( n_i \) is represented by \( \Pi \), and the convergence conditions of the bilevel model:

\[ \frac{\partial R_i(\mathbf{P})}{\partial \Pi} < \varepsilon \]  

(15)

Where \( \varepsilon \) is a small constant for convergence determination.

5. Experimental results and discussions

5.1 Gaming example

To study the clearing situation of the game model with the IEEE14 system as an example, the model topology diagram is shown in Figure 1. The basic data of the total load of the system is shown in Table 1, which is a fixed value. The actual total load of each round of simulation is based on the load constant \( d \) in Table 1, and an additional random variable is added. The value range of the random fluctuation variable is \([-0.05d, 0.05d] \), that is, the total load has a 10% fluctuation range to simulate the fluctuation of the actual load. Therefore, the unit's decision needs to consider the load fluctuations. To approximate the actual situation in Chinese electricity spot market, the proposed method is used to model day-ahead market in which each generation unit submits one bid curve for all 24h and the demand is considered as inelastic a curve. So in this paper, it is assumed the only strategic players are generation.
Table 1. System load baseline data.

| Time | Load d | Time | Load d | Time | Load d |
|------|--------|------|--------|------|--------|
| T1   | 720    | T9   | 720    | T17  | 896    |
| T2   | 664    | T10  | 760    | T18  | 768    |
| T3   | 600    | T11  | 800    | T19  | 696    |
| T4   | 576    | T12  | 768    | T20  | 632    |
| T5   | 560    | T13  | 720    | T21  | 576    |
| T6   | 528    | T14  | 808    | T22  | 560    |
| T7   | 560    | T15  | 920    | T23  | 608    |
| T8   | 640    | T16  | 952    | T24  | 680    |

The game simulation sets up five power generation units. By tuning of their bidding function's parameters $m_i$ and $n_i$, the unit plays learn to promote their strategies through the interactions of market clearing considering their total cost and market competition. The physical parameters and cost characteristics of the units are shown in Table 2 for details. The upper limit of the bidding price is set to 1000 ¥/MW. In order to simulate the current domestic power spot market situation, a unit has the same bidding function in all periods of the same round [22]. In order to simplify the analysis, it is assumed that the unit bidding is formulated as a linear function.

Table 2. Parameters of units.

| Units | Bus | P-min/MW | P-max/MW | TC Parameter - a | TC Parameter - b | TC Parameter - c |
|-------|-----|----------|----------|------------------|------------------|------------------|
| U1    | 1   | 0        | 240      | -0.25            | 350              | 0                |
| U2    | 2   | 0        | 240      | -0.22            | 325              | 0                |
| U3    | 3   | 0        | 320      | -0.125           | 320              | 0                |
| U4    | 8   | 0        | 300      | -0.14            | 320              | 0                |
| U5    | 6   | 0        | 150      | -0.3             | 360              | 0                |

Figure 1. IEEE 14-node system.
5.2. Simulation analysis

After multiple rounds of game simulation, the change of the bidding parameter \( m \) of each unit is shown in Figure 2, the change of parameter \( n \) is shown in Figure 3, the profit of each unit's simulation game is shown in Figure 4 and the units output is shown in Figure 5. \( m_i \) and \( n_i \) are the bidding parameters in equation 12.

It can be seen from Figure 2 and Figure 3 that the initial stage of the game of the market power units is in an obvious fluctuation state, and it is difficult for the market to achieve a steady-state equilibrium in a short time. The reason is that 1) the cost function of each market entity is inconsistent, and the bidding function of each unit is in the trial process; 2) the marginal cost of power generation of each unit is monotonically decreasing causing the optimization becomes a nonconvex programming; 3) more units bring more complexity to the market game, and the market clearing is affected by more factors. Among them, the fluctuation of the bidding parameter \( m \) of the unit 5 is the most obvious because its power generation capacity is small and it is most susceptible to the market price.

In the further game process, each genset generally adopts two bidding ideas. One is to submit low price biddings to obtain higher power output. Due to the higher electricity output, the overall cost of electricity generation has been reduced due to the cost characteristics, and it can be profitable to a certain extent.

The second is to submit a high price with a lower power output. The unit adopting this strategy is usually a marginal clearing unit. Due to its high bidding price, the market price is raised, thereby unit can achieve profitability. It can be clearly seen from the simulation results that the first strategy is adopted by unit 1, and the second strategy is adopted by units 2, 3, 4, and 5.

After multiple rounds of games, the bidding parameters of each unit tended to stabilize, and the market game entered an equilibrium state. Due to the characteristics of its own bidding, unit 1 quickly occupied the main market share in the game, and profited by seizing the electricity through low bidding price. Although other units have a relatively low power output, they can obtain high profits by submitting high bidding price. Unit 2, 3, 4, and 5 are also marginal clearing units which together directly determine the market price in most of the time periods. However, the final clearing price will not increase without limit due to the market competition, but it is actually stable at a high market price.

In this model, once one of the units adopts the strategy of low bidding price with high power output to seize the market share, the other units as "rational people" [23] usually do not adopt the same strategy because it usually results in a loss of both profits.

![Figure 2. Change of unit bidding parameter m.](image-url)
In the end, the units that adopt the strategy of low-cost preemption in this model have higher profits. The reason is that, under the rules of clearing marginal electricity prices, unit bidding information is not shared, while units that adopt high-price strategies to obtain high profits, and inadvertently making the units adopting low-price strategies obtain high profit. And under the characteristic of marginal diminishing cost, higher unit output will make its power generation cost lower.

In addition, the final equilibrium clearing price of the market is usually 1.5-3 times the actual cost of the unit with high deviation. Due to the diminishing marginal cost of gensets, it is not possible to make biddings according to unit cost characteristics. The market will encourage units to choose variable strategies to participate in market competition. And the market clearing price is determined by high-price biddings and market competition.
6. Conclusions
The research describes the bidding strategy of power units’ spot market based on the decreasing marginal cost through calculation examples, and analyzes the incentive effect of market regulations on its bidding behavior. Simulation experiments show that in monotonically increasing generation bidding rule, units with decreasing marginal cost no longer meet the incentive compatibility under the marginal price settlement. The existing mechanism will incentivize units to declare biddings that seriously deviate from their true costs, and may eventually result in a market equilibrium clearing price that is much higher than the true cost of the unit. The price for bidding will seriously block the reasonable spot market price signal. The market price does not reflect the real cost of power generation, but reflects the price trial of power units seeking high profits. In the absence of competition or collusion, the market price easily reaches the price ceiling set by the market. Therefore, based on the above background, it is necessary to establish an electricity competition market that aims at the diminishing marginal cost of power generation and restore the characteristics of market prices that reflect the true cost.

References
[1] Deqing Gan, Donghan Feng, Jun Xie 2013 Electricity markets and power system economics[M] Boca Raton USA: CRC Press
[2] PJM. Manual 11:Energy & Ancillary Services Market Operations[EB/OL].Valley Forge, PA: PJM, 2019 [2019-3-12]. http://www.pjm.com/library/manuals.aspx
[3] CAISO. Business Practice Manual for Market Operations[EB/OL] . Folsom , CA : CAISO, 2017 [2018-11-8].
[4] E. Litvinov 2010 Design and operation of the locational marginal prices-based electricity markets [J]. IET Generation, Transmission & Distribution (2) 315-323
[5] F. C. Schwepppe, M. C. Caramanis, R. D. Tabors, R. E. Bohn 1988 Spot Pricing of Electricity [M]. Bosston, MA: Kluwer
[6] Li Lin, Lanqing Zou, Zhou Peng, Xinyu Tian 2017 Multi-angle Economic Analysis on Deep Peak Regulation of Thermal Power Units With Large-scale Wind Power Integration [J] Automation of Electric Power Systems 41(07) 21-27
[7] Linli Da, Xinyu Tian 2017 Analysis of Deep Peak Regulation and Its Benefit of Thermal Units in Power System With Large Scale Wind Power Integrated [J] Power System Technology 41(07) 255-2263
[8] Z. Yang, T. Zheng, J. Yu and K. Xie 2019 A Unified Approach to Pricing under Non-convexity [J] IEEE Transactions on Power Systems. doi: 10.1109/TPWRS.2019.2911419.

[9] Yi Huang, Yubo Zhang 2010 Effect Evaluation of Incentive Mechanism in Electricity Market Environment [J] Power System Technology 34(09) 122-126

[10] Xiaodong Zhang 2005 Power Genenet'r's Cost Analysis And Market Competition Strategies [D]. North China Electric Power University

[11] Ziyu Chen 2019 Study on Power Plant Competition Strategy in Spot Market [D]. South China University of Technology

[12] Heng Feng, Zhenglin Yang, Yaxian Zhenhg, Fei Ye, Xu Zhanag, Xin Shi 2018 Intelligent Agent Based Bidding Simulation Method for Multi-input Decision Factors of Power Supplier [J] Automation of Electric Power Systems 42(23) 72-80

[13] Jiazhí Zeng, Xiongfei Zhao, Jing Li, Gang Li, Kangjing Li, Zhenbo Wei 2017 Game Among Multiple Entities in Electricity Market with Liberalization of Power Demand Side Market [J] Automation of Electric Power Systems 41(24) 129-136

[14] Shuai Wang Generators’ Bidding Strategies in the Day-ahead Market Based on Q-Learning Algorithm [J] Electric Power Technologic Economics 22(03) 34-39

[15] Zhan Gao, Yiqun Song 2008 Power Supplier Bieding Strategies Based on Q-learning Algorithm [J] East China Electric Power 04 20-22

[16] Chunhua Peng, Kun Qian, Junli Yan 2019 A Bidding Strategy Based on Differential Evolution Game for Generation Side in Power Grid Integrated With Renewable Energy Resources [J] Power System Technology 43(06) 2002-2010

[17] Salehizadeh, Mohammad Reza, Rahimi-Kian Ashkan, Hausken Kjell 2016 A Leader–Follower Game on Congestion Management Springer Vol 2

[18] Salehizadeh Mohammad Reza, and Salman Soltaniyan 2016 Application of fuzzy Q-learning for electricity market modeling by considering renewable power penetration [J] Renewable and Sustainable Energy Reviews 56 1172-1181

[19] Kiannejad, Mohammad, et al 2020 Artificial neural network approach for revealing market competitors’ behaviour IET Generation, Transmission & Distribution 14(7) 1292-1297

[20] Zhiqiang Yuan, Zhijian Hou, Chuanwen Jiang, Yiqun Song 2004 Analysis of Cournot Equilibrium In Hydrothermal Power System [J] Automation of Electric Power Systems 04 17-21

[21] Dan Li, Junyong Liu, Youbo Liu, et 2015 Analysis on Electricity Market Linkage Game Considering Participation of Wind Power and Energy Storage [J] Power System Technology 39(4) 1001-1007

[22] Junce Ding, Ke Shi, Haoyong Chen, Wei Chen, Zhifei Liang 2018 Analysis on Monthly Electricity Bidding of Guangdong Based on Experimental Economics [J] Guangdong Electric Power 31(06) 19-24

[23] Tianqun Pan 2003 The Dilemma of the Rational Person Hypothesis in Game Theory [J] Economist 04 99-104