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Development of Optimal Bidding Strategies for Generation Companies in Electricity Markets Based on Fuzzy Set Theory

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ABSTRACT

The power industry restructuring is undergoing in many countries around the world and as a result many electricity markets have been established. In the electricity market environment, profits of generation companies depend, to a large extent, on bidding strategies employed. Hence, how to develop optimal bidding strategies has become a major concern of generation companies. In this paper, a fuzzy set theory based method for building optimal bidding strategies is presented for generation companies participating in a recently established electricity market in which the widely-used step-wise bidding protocol is utilized and the available historical data is not sufficient. Taken into account of the insufficient history data especially bidding data, bidding behaviors of rival generation companies are modeled as fuzzy sets and a bidding strategy optimization model is then developed. The well-known genetic algorithm is next employed to solve the bidding strategy optimization problem. Finally, a simple numerical example with five generation suppliers participating in an electricity market is served for illustrating the essential features of the presented method.

1. INTRODUCTION

The power industry restructuring is undergoing in many countries around the world, and as a result, competition has been introduced in the generation sector through bid-based operation. In the new and competitive environment, profit-maximization is a primary objective of generation companies or power suppliers. Theoretically, in a perfectly competitive electricity market, all power suppliers are price takers, and the optimal bidding strategy for them is simply to bid their marginal costs. However, it is well known that the emergent electricity market structure is more akin to oligopoly than perfect market competition, due to special features of the electricity supply industry such as: a limited number of producers, large investment size (barrier to entry), transmission constraints and transmission losses. In an oligopoly market, the profit of a supplier depends, to a great extent, on his own strategies and his rivals' strategies as well. Without exception, in an electricity market bidding strategies employed by generation companies may have significant impacts on their own profits, and on the operating behaviors of the market as well. Hence, how to develop optimal bidding strategies for generation companies or how to analyze strategic behaviors of them and hence to figure out the potential market power abuse is now a very active research area.

How to develop optimal bidding strategies for competitive generation companies or how to examine potential strategic behaviors of generation companies so as to assess market power is now a very active research area and considerable amount of literature [1-7] has been published on this subject in recent years, and in ref. [1] a comprehensive survey was made. Broadly speaking, there are basically three ways for developing optimal bidding strategies. The first one relays on estimations of the market clearing price (MCP) in the next auction/trading period. The second approach is game theory based, while the third one utilizes estimations of bidding behaviors of rival participants. Most publications available are based on the third line of approaches, and the research work carried out in this paper belongs to this kind. In this approach, an optimal bidding strategy is developed by estimating rivals' bidding behaviors based on history data of market prices, load and rivals' bidding parameters. In [2,3], rival' bidding behaviors are modeled by probability distribution functions, and this is workable for mature electricity markets with sufficient history data. However, for recently launched electricity markets or those markets in which auction or bidding rules were modified recently, available data may not be sufficient for probabilistic modeling of rivals' bidding behaviors. By recognizing this problem, it is proposed in some papers such as [8] that fuzzy sets based methods are more appropriate for this purpose. However, the research work in this area is still very preliminary and a systematic method has not been developed up to now.

In this paper, the problem of developing optimal bidding strategies for generation companies participating in Zhejiang provincial electricity market in China is investigated. In this market, the step-wise bidding protocol is utilized. Based on available information, such as historical bidding data, the data available before the power industry restructuring (such as rivals' generator types and corresponding operating efficiencies), current fuel prices, and experts' heuristic knowledge, the well-developed fuzzy set theory is employed to model the estimated bidding behaviors of competitors, and a bidding strategy optimization model is then developed and a genetic algorithm based solving method employed. Finally, a sample example with five generation companies participating in an electricity market is served for demonstrating the essential features of the approach.

2. THE ELECTRICITY MARKET STUDIED

While the restructuring model of the power industry in China is still under extensive discussions, the Zhejiang Provincial power system has been selected to make trial market operation since January 1, 2000. This market has been in operation, basically smoothly, for more than two years. As a model system, the operation result of this market will provide an important guidance for the future restructuring efforts in China. Given this background, research work here is done basically based on the market protocol of the Zhejiang Provincial electricity market, although, as a preliminary study, many simplifications are made.

The current Zhejiang provincial electricity market is based on the well-known single buyer model. Several generation companies (GENCOs) participate in the bid-based operation, and Zhejiang Power Company, acting as the single buyer, purchases power from GENCOs based on load forecast and bids from GENCOs, and sells to consumers. Zhejiang power dispatching center is responsible for market trading and system operation. The power trading is done daily, and each day is divided into 48 auction/trading periods, i.e. each trading period is for 30 minutes. Registered units of each GENCO are required to bid separately. Before the next trading day starts, bidding for the 48 periods in the next day is conducted every day. Each GENCO can bid at most I blocks for each period (currently $I=10$ in Zhejiang provincial electricity market). The block price must be non-decreasing with the increase of the block number. The dispatched output level of each generator in each period is determined based on the bided prices and load forecasted, and the cheapest blocks which can meet the load demand are selected and the price of the block selected last sets the market clearing price (MCP).

3. PROBLEM FORMULATION

To simplify the presentation and without loss of generality, assume that each GENCO has only one registered unit. Futher, suppose that the system to be studied consists of $N+1$ independent GENCOs and GENCO X is our subject of study, hence, there are N rivals in the market. Although GENCO X could bid I blocks for each trading period under the bidding protocol, in an electricity market employing the uniform MCP, if the risk associated with the bidding is not taken into account, it is only necessary for GENCO X to bid one optimal price for one block only. In this case, bidding more than one block with different prices does not make any sense. Hence, the problem of developing an optimal bidding strategy for GENCO X is simplified to the one of determining an optimal bidding price P for its available capacity Q. On the other hand, each rival GENCO may bid I blocks for the purpose of mitigating risks. Suppose that the nth rival bids I blocks with block capacity and block price as follows: the first block with block capacity $\tilde{Q}_1{}^n$ and block price $\tilde{P}_1{}^n$, the second block with block capacity $\tilde{Q}_2{}^n$ and block price $\tilde{P}_2{}^n$,…, and so on. The system load is represented by D.

As a preliminary investigation, in this work bidding strategies are developed for one-period (half hour) auction only, and hence inter-temporal operating constraints for a generator, such as the minimum up and down times and the maximum number of start-ups and shutdowns allowed, are not accounted for. Thus, the aim of this work is to develop an optimal bidding strategy for GENCO X in the next auction/trading period, and for this purpose it is necessary to estimate rivals' bidding behaviors. Although it is impossible to know rivals' bidding strategies before the market auction clears, it is possible to estimate rivals' bidding behaviors based on available information, such as historical data of market clearing prices, system loads, rivals' bidding parameters, data available before the power industry restructuring (such as rivals' generator types and corresponding operating efficiencies) and experts' heuristic knowledge. For this purpose, the well-developed fuzzy set theory is a good alternative. Many kinds of fuzzy sets are available such as the single point fuzzy set, triangle fuzzy set and Gauss fuzzy set, and in this work the widely-used Gauss fuzzy set is employed to model rivals' bidding behaviors.

As a preliminary investigation, suppose that, from GENCO X's point of view, the bidding block capacities of the nth rival $(n=1,2,\&,N)$, $\tilde{Q}_i{}^n$ $(i=1,2,\&,I)$ in the next auction period, are known. In practice, this may be quite difficult and estimations or predictions based on historical data are inevitable. Further, rivals' bidding block prices are represented by fuzzy sets $\tilde{P}_i{}^n = \{x_i{}^n\}$ and Gauss functions are employed as membership functions defined on the domain $\left[\tilde{P}_{i\,min}{}^n, \tilde{P}_{i\,max}{}^n\right]$ as follow:

$$\mu_{\tilde{P}_i^n}\left(x_i{}^n\right) = e^{-\frac{\left(x_i{}^n - C_{\tilde{P}_i^n}\right)^2}{2\sigma_{\tilde{P}_i^n}{}^2}} \qquad \left(i = 1,2,\cdots,I;\, n = 1,2,\cdots,N\right) \tag{1}$$

Here, $C_{\tilde{P}_i^n}$ denotes centers and $\sigma_{\tilde{P}_i^n}$ spreads or widths of fuzzy sets, which respectively correspond to the well-known expectations and standard deviations of stochastic variables. In order to simplify the calculation process, discretization is made about the domain. Specifically, M random numbers are generated in $\left[\tilde{P}_{i\,min}{}^n, \tilde{P}_{i\,max}{}^n\right]$, and denoted as $x_i{}^n(1), x_i{}^n(2), \cdots, x_i{}^n(M)$. M is a large positive integer. The fuzzy set $\tilde{P}_i^n$ is then defined on the discrete domain $\left[x_i{}^n(1), x_i{}^n(2), \cdots, x_i{}^n(M)\right]$, with respective membership functions calculated using Eq. (1) as $\mu_{\tilde{P}_i^n}\left(x_i^n(1)\right), \mu_{\tilde{P}_i^n}\left(x_i^n(2)\right), \cdots, \mu_{\tilde{P}_i^n}\left(x_i^n(M)\right)$. Hence, the fuzzy set $\tilde{P}_i^n$ can be represented as follow:

$$\tilde{P}_i^n = \frac{\mu_{\tilde{P}_i^n}\left(x_i^n(1)\right)}{x_i^n(1)} + \frac{\mu_{\tilde{P}_i^n}\left(x_i^n(2)\right)}{x_i^n(2)} + \cdots \frac{\mu_{\tilde{P}_i^n}\left(x_i^n(M)\right)}{x_i^n(M)} = \sum_{m=1}^{M} \frac{\mu_{\tilde{P}_i^n}\left(x_i^n(m)\right)}{x_i^n(m)} \tag{2}$$

Now, combine the I fuzzy sets representing I bidding block prices of the nth rival into a fuzzy set vector $\tilde{P}^n$, i.e. $\tilde{P}^n = \left(\tilde{P}_1^n, \tilde{P}_2^n, \cdots, \tilde{P}_I^n\right)$, on a discrete space with I dimensions. Hence, the fuzzy set vector $\tilde{P}^n$ describes the nth rival' bidding behavior completely (as mentioned before, bidding block capacities are supposed to be known and fixed) with the following expression,

$$\tilde{P}^n = \frac{\mu_{\tilde{P}^n}\left(X^n(1)\right)}{X^n(1)} + \frac{\mu_{\tilde{P}^n}\left(X^n(2)\right)}{X^n(2)} + \cdots \frac{\mu_{\tilde{P}^n}\left(X^n(M)\right)}{X^n(M)} = \sum_{m=1}^{M} \frac{\mu_{\tilde{P}^n}\left(X^n(m)\right)}{X^n(m)} \tag{3}$$

Here, $X^n(m) = \left(x_1^n(m), x_2^n(m), \cdots, x_I^n(m)\right)$ is a vector and its membership function $\mu_{\tilde{P}^n}\left(X^n(m)\right)$ can be calculated by the well-established fuzzy intersection operation as follow:

$$\mu_{\tilde{P}^n}\left(X^n(m)\right) = \mu_{\tilde{P}_1^n}\left(x_1^n(m)\right) \wedge \mu_{\tilde{P}_2^n}\left(x_2^n(m)\right) \wedge \cdots \mu_{\tilde{P}_I^n}\left(x_I^n(m)\right) \tag{4}$$

Further, combine all N fuzzy set vectors representing N rivals' bidding behaviors into a fuzzy set matrix $\tilde{P}$, i.e. $\tilde{P} = \left(\tilde{P}_1, \tilde{P}_2, \cdots, \tilde{P}_N\right)$, defined on a discrete space with $N \times I$ dimensions. Thus, the fuzzy set $\tilde{P}$ models all rivals' bidding behaviors and can be expressed as:

$$\tilde{P} = \frac{\mu_{\tilde{P}}\left(X(1)\right)}{X(1)} + \frac{\mu_{\tilde{P}}\left(X(2)\right)}{X(2)} + \cdots \frac{\mu_{\tilde{P}}\left(X(M)\right)}{X(M)} = \sum_{m=1}^{M} \frac{\mu_{\tilde{P}}\left(X(m)\right)}{X(m)} \tag{5}$$

Here, $X(m) = \left(X^1(m), X^2(m), \cdots, X^N(m)\right)$ is a matrix of $N \times I$ dimensions and its membership function $\mu_{\tilde{P}}\left(X(m)\right)$ can be calculated by the fuzzy intersection operation as well,

$$\mu_{\tilde{P}}\left(X(m)\right) = \mu_{\tilde{P}^1}\left(X^1(m)\right) \wedge \mu_{\tilde{P}^2}\left(X^2(m)\right) \wedge \cdots \mu_{\tilde{P}^N}\left(X^N(m)\right) \tag{6}$$

Up to here, all rivals' bidding behaviors are represented by fuzzy sets, and GENCO X can then develop its own optimal bidding strategy. Obviously, GENCO X's profit depends, to a great extent, on both its own bidding strategy and rivals' bidding strategies, and hence its profit is also a fuzzy variable (denoted by a fuzzy set R) defined on a discrete space $\left[r(1), r(2), \cdots, r(M)\right]$. Of course, at the end the fuzzy variable R needs to be defuzzified into a crisp variable $\hat{r}$. Hence, for GENCO X, the profit maximization objective for building an optimal bidding strategy can be mathematically described as:

$$\underset{P}{Maximise} \quad \hat{r} \tag{7}$$

Subject to:

$$0 \le q \le Q \tag{8}$$

$$P_{min} \le P \le P_{max} \tag{9}$$

This is to determine block price P so as to maximize the profit $\hat{r}$ subject to Eqs. (8) and (9) q is GENCO X's dispatched output. P_{min} and P_{max} are the lower and upper bidding price limits allowed by the market rules. While P is not explicitly appeared in Eq. (7), it is implicitly included in the process of determining $\hat{r}$. In the next section, a method to determine $\hat{r}$ will be introduced.

4. SOLUTION METHOD

4.1 Calculation of $\hat{r}$

The fuzzy set R defined on a discrete space $[r(1), r(2), \cdots, r(M)]$ can be described as follow:

$$R = \frac{\mu_R(r(1))}{r(1)} + \frac{\mu_R(r(2))}{r(2)} + \cdots \frac{\mu_R(r(M))}{r(M)} = \sum_{m=1}^{M} \frac{\mu_R(r(m))}{r(m)} \tag{10}$$

Now, let us look at how to calculate the element $r(m)$ of the fuzzy set R as showed in Eq. (10) and its membership function $\mu_R(r(m))$.

Given the rivals' bidding price fuzzy set $\tilde{P} = \sum_{m=1}^{M} \frac{\mu_{\tilde{P}}(X(m))}{X(m)}$, we can take any element $X(m)$ from it and suppose all bidding block prices of N rivals are $x_1^1(m), x_2^1(m), \&, x_I^1(m), x_1^2(m), x_2^2(m), \&, x_I^2(m), \& \&, x_1^N(m), x_2^N(m), \&, x_I^N(m)$. In this case, when GENCO X's bidding price is P, its profit $r(m)$ is determined by its own bidding price P and rivals' bidding prices $X(m)$, i.e. $r(m) = f(P, X(m))$. $r(m)$ can be calculated as follow:

$$r(m) = \lambda \times q \times t - C(q,t) \tag{11}$$

C is the production cost function of GENCO X. t is the trading period duration and here $t = 0.5\ h$. λ is the market clearing price of the trading period studied. The power dispatching center ranks all generators' bidding block prices, i.e. $x_1^1(m), x_2^1(m), \&, x_I^1(m), x_1^2(m), x_2^2(m), \&, x_I^2(m), \& \&, x_1^N(m), x_2^N(m), \&, x_I^N(m)$ from low to high. The dispatched output level of each generator can then be determined based on the bided prices and load forecasted. The last dispatched block sets the market clearing price λ. The generation cost function is generally described as a quadratic function,

$$C(q,t) = \left(a + bq + cq^2\right) \times t \quad (12)$$

a, b and c are generation cost function coefficients.

The membership function of $r(m)$, $\mu_R(r(m))$, can be obtained as follow:

$$\mu_R(r(m)) = \mu_{\tilde{P}}(X(m)) \quad (13)$$

Finally, the fuzzy set R should be defuzzified to a crisp variable $\hat{r}$ and the widely-used weighted average method is employed here,

$$\hat{r} = \frac{\sum_{m=1}^{M} r(m)\mu_R(r(m))}{\sum_{m=1}^{M} \mu_R(r(m))} \quad (14)$$

When GENCO X's bidding price is P, the detailed procedure of calculating GENCO X's profit $\hat{r}$ is listed below:

a) Specify M.
b) Set element counter $m = 0$.
c) Randomly generate an element $x_i^n(m)$ of the fuzzy set $\tilde{P}_i^n$ from $\left[\tilde{P}_{i\,min}{}^n, \tilde{P}_{i\,max}{}^n\right]$ $n=1,2,\&,N;$ $i=1,2,\&,I$ and calculate the membership function $\mu_{\tilde{P}_i^n}\left(x_i^n\right)$ using Eq. (1).
d) Combine $x_i^n(m)$ $n=1,2,\&,N;$ $i=1,2,\&,I$ into a vector $X(m)$ of a fuzzy set $\tilde{P}$ and calculate its membership function $\mu_{\tilde{P}}(X(m))$ using Eqs. (4) and (6).
e) Calculate $r(m)$ of the fuzzy set R using Eq. (11), and its membership function $\mu_R(r(m))$ by Eq. (13).
f) Set $m = m+1$.
g) If $m<M$ go back to c, otherwise go to h.
h) Calculate GENCO X's profit $\hat{r}$ using Eq. (14).

4.2 A genetic algorithm based method for solving the optimal bidding strategy problem

The problem of building the optimal bidding strategy for GENCO X, as described by Eq. (7) through Eq. (9), is a discrete nonlinear optimization problem and can be solved by the well-known genetic algorithm [9]. Details of the genetic algorithm will not be given here for saving space. Please refer to ref. [9] if needed.

5. NUMERICAL EXAMPLES

A simple example with five GENCOs including GENCO X is used to illustrate the essential features of the proposed method. As mentioned before, GENCO X is our subject of research and hence there are four rivals (i.e. $N = 4$) in the market. The capacity of GENCO X is Q = 600 MW, generation cost function coefficients in Eq. (12) are $a = 0$, $b = 2.0$, $c = 0.01125$, and permitted bidding price lower and upper limits $P_{min} = 0$ and P_{max} = 60.0\$/MWh. Suppose each GENCO is permitted to bid, at most, three blocks (i.e. $I = 3$).

Many test cases are carried out, but only simulation results for two cases are given below:

5.1 Case 1

Suppose that the capacities of the 4 rivals are the same as that of GENCO X, i.e. 600 MW each, and that each rival bids 3 blocks and the allocated capacities among the 3 blocks are the same, i.e. $\tilde{Q}_i^n = 200\ MW$ $(n = 1,2,3,4;\ i = 1,2,3)$. The membership function of the fuzzy set $\tilde{P}_i^n$ representing each rival's bidding block price is Gauss function $\mu_{\tilde{P}_i^n}$ as shown in Eq. (1), and the center $C_{\tilde{P}_i^n}$ and width $\sigma_{\tilde{P}_i^n}$ for all rivals are respectively the same for each block, as listed in Table 1. In practice, these fuzzy parameters should be estimated based on history data of rivals' bidding parameters, loads, market clearing prices and experts' heuristic knowledge.

Table 1 Rivals' bidding parameters in Case 1

$n = 1,2,3,4$	Block1	Block 2	Block 3
$\tilde{Q}_i^n$ (MW)	200	200	200
$C_{\tilde{P}_i^n}$ (\$/MWh)	10.0	30.0	50.0
$\sigma_{\tilde{P}_i^n}$ (\$/MWh)	3.0	3.0	3.0

Take M =10000, and the parameters associated with the genetic algorithm [9] are specified as follows: population is 80, crossover probability 0.7, mutation probability 0.1, and the maximum permitted number of iterations 100. The fitness function of the genetic algorithm is defined as the crisp variable $\hat{r}$ of the fuzzy set R representing GENCO X's profit and can be obtained by using the calculation process detailed in Section 4.1. When the load D =2000 MW, the optimal bidding price for GENCO X obtained by the proposed method is $P^* = 34.33\ \$ / MWh$ and the corresponding profit is \$7244.

5.2 Case 2

The capacities of all five GENCOs are the same as those in Case 1, i.e. 600 MW each, and the block capacities of the four rivals, i.e. $\tilde{Q}_i^n$ $(n = 1,2,3,4;\ i = 1,2,3)$, are also the same as those in Case 1, i.e. 200 MW each. However, the center $C_{\tilde{P}_i^n}$ of the membership function $\mu_{\tilde{P}_i^n}$ of the rivals' block prices $\tilde{P}_i^n$ are no longer the same, as listed in Table 2.

Table 2 Rivals' bidding parameters in Case 2

		Rival 1 (n=1)	Rival 2 (n=2)	Rival 3 (n=3)	Rival 4 (n=4)
Block 1	$\tilde{Q}_1^{\,n}$ (MW)	200	200	200	200
	$C_{\tilde{P}_1^n}$ (\$/MWh)	5	8	10	12
	$\sigma_{\tilde{P}_1^n}$ (\$/MWh)	3.0	3.0	3.0	3.0
Block 2	$\tilde{Q}_2^{\,n}$ (MW)	200	200	200	200
	$C_{\tilde{P}_2^n}$ (\$/MWh)	25	28	30	32
	$\sigma_{\tilde{P}_2^n}$ (\$/MWh)	3.0	3.0	3.0	3.0
Block 3	$\tilde{Q}_3^{\,n}$ (MW)	200	200	200	200
	$C_{\tilde{P}_3^n}$ (\$/MWh)	45	48	50	52
	$\sigma_{\tilde{P}_3^n}$ (\$/MWh)	3.0	3.0	3.0	3.0

The parameters associated with the genetic algorithm are the same as those in Case 1. When the load is specified to be 2000 MW, 2200 MW and 2400 MW, by solving the bidding optimization problem described by Eq.(7) through Eq.(9) the optimal bidding price for GENCO*X* is 34.53, 39.93 and 41.02 \$/MWh, and the corresponding profit \$6982, \$8727 and \$10274, respectively. From these test results, it is obvious that the larger the load is, the higher the optimal bidding price will be, and as a result, the larger the MCP and the GENCO X's profit will be.

6. CONCLUDING REMARKS

A method is proposed for building the optimal bidding strategy for generation companies participating in recently launched or market structure and auction rules just modified electricity markets in which the available historical data is not sufficient. The well-established fuzzy set theory is used to model competitors' bidding behaviors, and an optimal bidding strategy model for generation companies is then developed and finally solved by the genetic algorithm. An illustrative example with five generation companies participating in an electricity market is served for illustrating the essential features of the proposed method. As a preliminary research work, inter-temporal operating constraints for start-up and shutdown of generators and transmission congestion are not taken into account, and these will be done in later studies. It should be stressed that the emphasis of this work is on establishing a framework for building optimal bidding strategies for generation companies with imperfect and insufficient information, rather than on developing a method for estimating rivals' bidding behaviors.

7. ACKNOWLEDGEMENTS

This work is jointly supported by the Research Grant Committee (RGC HKU 7173/03E) of Hong Kong Government and a seed funding project from the University of Hong Kong.

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