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Biding Strategy in Restructured Environment of Power Market Using Game Theory

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ABSTRACT

In the restructured environment of electricity market, firstly the generating companies and the customers are looking for maximizing their profit and secondly independent system operator is looking for the stability of the power network and maximizing social welfare. In this paper, a one way auction in the electricity market for the generator companies is considered in both perfect and imperfect competition cases. A new model is provided to use the historical data of power market in the state of competition with imperfect information in which two probability functions were simultaneously used for the estimation of required information about each generator company. Nash equilibrium in the game theory is used to find the stability point in the biding strategy of generator companies. The effect of network conditions like limitation of transmission lines, network load, maximum generation of each generator company and the imperfect estimation of information about other competitors on the profit of generator companies and also on the market power of the generators in two mentioned competition methods were shown in the numerical simulation.

1. Introduction

Previously, the structure of power industry was as monopoly and in this structure, generation companies (GENCOs), customers, distribution network and the transmission network were all in hands of one authority. Electricity as a good with known price from GENCOs to customers was transmitted. Because of the monopolistic condition at that time, no competition was observed in buying and selling the power. After some time, the structure of power industry has entered a restructured environment which has changed the monopolistic condition to oligopolistic. In this condition, an electricity market was created which resulted in the formation of GENCOs and consuming companies who have traded the energy in this market. In these conditions, each participant, was looking for maximizing the profit and this resulted in competition in the power market.

One of the famous markets of today, was the pool-based power market. It was such that every company offers the proposals for trading the power to the market operator. If both of the GENCOs and customers give their proposals to the market operator, then a two way auction will be created in the power market [1]. In some cases when the sensitivity of customers to the price of power energy is zero, only the GENCOs give their offers to the market operator and a one way auction will be created in the market [2]. GENCOs in power market can give their proposals as the quantity produced power which is also capable of being sold and the price of that quantity to the market operator. According to the rules of power market, GENCOs could use two methods of uniform price [3] and pay as bid [4] to price their power which can be sold. After sending the proposals by GENCOs and customers to the pool based market operator, which is an independent system operator (ISO), ISO clears the market while considering power network constraints, quantity of load, keeping stability of power network and maximizing the social welfare. After cleaning the market, ISO determines the quantity of power that can be sold and bought and its price for each participant in the market [5, 6]. One of the most famous models for GENCOs proposals is the supply function equilibrium (SFE) model. In this model, every GENCO determines the price and quantity for its generation [7, 8]. In the one way auction of power market, maximizing the social welfare from ISO is the same as minimizing the revenue of GENCOs. Therefore each GENCO considering the fact that the amount of demand is constant, will look for the best strategy for proposing sells to be able to maximize its profit. It should be mentioned that the proposals of each GENCO is dependent and affective on the proposals of other competitors [9]. Competition between GENCOs in the power market can be presented in the form of a game. In fact, each GENCO, can find its optimized strategy using Nash equilibrium in the game theory [10]. By information, competition between GENCOs in two branches of game with perfect and imperfect information is investigated [6, 11]. One of the factors affecting the proposals of GENCOs, is the amount of market power of that GENCO. The market power is dependent of the conditions of GENCO and the place of that GENCO in the power market. Different indices were used to determine the market power amongst one which was Herfindahl-Hirschman Index (HHI) [12]. Conditions of the network could be so to decrease or increase the market power. One of the factors which improves the market power of GENCOs and results in the increase in price of electricity, was the limitation of transmission lines [13]. In this paper, a one way auction in the electricity market for the generator companies is considered in both perfect and imperfect competition cases. A new model is provided to use the historical data of power market in the state of competition with imperfect information in which two probability functions were simultaneously used for the estimation of required information about each generator company. Nash equilibrium in the game theory is used to find the stability point in the biding strategy of generator companies.

2. GENCO'S BID

Lots of models have been proposed to GENCOs proposals in the power market like Bertrand, Carnot and Stackelberg models [11]. In this article, the common model of SFE is used to GENCOs proposals. In this model, every GENCO determines the price and quantity for its generation. Cost function of GENCOs is as a second order function as follows:

$$C_i = a_i p_i^2 + b_i p_i + c_i \quad i = 1, 2, \ldots, n_g \tag{1}$$

In which n_g is the number of GENCOs, p_i is the generated power of i^{th} GENCO and a_i, b_i and c_i are the constant coefficients of cost function of the i^{th} GENCOs.

Marginal cost (MC) of the ith GENCOs which is a linear function of quantity of generated power of that GENCOs and is as follows:

$$MC_i = 2a_i p_i + b_i \tag{2}$$

Normally, the GENCOs use a linear function of their generation for pricing on production and is as follows:

$$f\,(p_i) = x_i\, p_i + y_i \tag{3}$$

In which f (p_i) is the pricing function and x_i and y_i are the coefficients of biding strategy for the ith GENCO. In the competitive conditions of power market, the GENCOs are looking for the best coefficients for the pricing functions to maximize their benefit, sell more power and for this power to have a suitable price. On the other hand, the quantity of power which is bought from each GENCO is vice versa dependent to the price of that GENCOs. For the strategy of pricing of the power generators, the k coefficient is used in this article [11]. Each ith GENCO can give their price using its optimized k_i as follows:

$$\begin{aligned} \Psi_i &= k_i \times MC_i \\ \Psi_i &= 2a_i k_i p_i + k_i b_i \end{aligned} \tag{4}$$

In which Ψ_i is the price function for the i^{th} GENCO, p_i is the generated power of i^{th} GENCO, k_i is the pricing strategy of i^{th} GENCO and MC_i is the marginal cost of i^{th} GENCO. According to equation (3), x_i and y_i are equal to $2a_ik_i$ and k_ib_i respectively.

In the power market, there exist two methods for the pricing of GENCOs as follow:

First Method: This is the uniform price method in which the GENCOs gives their proposals to ISO and after determination of price market by ISO, power will be bought for the equal price of market clearing price from all GENCOs.

Second Method: This is the pay as bid method in which after sending proposals by GENCOs to ISO, and market clearing by ISO, the power of the winner GENCOs of the market will be bought according to their proposed price [4]. Considering the limitations of the network, this price is the same as Local Marginal Price (LMP). In this article, the second method was used for the proposed price of GENCOs. Considering this method and linearity of the supply curve of GENCOs, the revenue of each GENCO is as follows:

$$
\begin{aligned}
R_i &= LMP_i \times p_i \\
R_i &= \int_0^{p_i} (2a_i k_i p_i + k_i b_i) dp_i \\
&= k_i (a_i p_i^2 + b_i p_i)
\end{aligned} \tag{5}
$$

In which R_i is the revenue of i^{th} GENCO in the pay as bid method and LMP_i is the local marginal price of i^{th} GENCO.

The participation of each GENCO in the power market is for obtaining the benefit and the GENCOs have always competed to each other to obtain the maximum benefit. The benefit function and the target function of each GENCO is as follows:

$$
\begin{aligned}
&\pi_i = R_i - C_i = (k_i - 1) \times (a_i p_i^2 + b_i p_i) - c_i \\
&\max \left\{ (k_i - 1) \times (a_i p_i^2 + b_i p_i) - c_i \right\}
\end{aligned} \tag{6}
$$

In which π_i is the benefit of i^{th} GENCO, R_i is the revenue of i^{th} GENCO and C_i is the cost of i^{th} GENCO. Since the quantity of power generated by each GENCOs is dependent on the proposed price of that company, then the main variable of the target function of GENCOs is the k coefficient.

3. MARKET CLEARING

In the restructured environment of power market, after sending the proposals of GENCOs and customers to ISO, the ISO will clear the market.

GENCOs and customers will send their proposals to ISO and ISO will obtain a supply curve amongst the proposals of GENCOs such that the GENCO with lower price is more suitable for selling the energy. Also ISO will obtain a demand curve such that the customer with higher price is more suitable for buying the power in the market. Afterwards, by intersection of the demand and supply curves, the share of buy or sell and the price of each participant in the market will be determined [7, 8].

ISO is an independent authority the goal of which is maintaining the stability of the power network and maximizing social welfare of participants in the power market. Since in this paper, the amount of demand is constant, then a one way auction will appear and ISO will minimize the revenue of GENCOs to maximize the social welfare. In this paper, for the purpose of stability of power network by ISO, DC power flow was used. In fact, the ISO formulates the market clearing problem by implementing a bid-based security-constrained economic dispatch (SCED) in which ISO according to condition of DC power flow, runs an economic dispatch for revenue of GENCOs [13]. In this paper, GENCOs faced with a double-layer problem to find their optimal biding strategy. In the first layer, each GENCO is looking for maximizing his profit and in the second layer, ISO clears the market by implementing a bid-based SCED.

The target function of ISO and the limitations of the power network is as follows:

$$
\begin{aligned}
&\min \sum_{i=1}^{n_g} LMP_i \times p_i \\
&s.t. \\
&B\theta = p_G - p_D \\
&p_i^{\min} \le p_i \le p_i^{\max} \qquad i = 1, \ldots, n_g \\
&F_l^{\min} \le F_l \le F_l^{\max} \qquad l = 1, \ldots, L
\end{aligned} \tag{7}
$$

In which n_g is the number of GENCOs, LMP_i is the local marginal price of i_{th} GENCO, p_i is the output power of i^{th} GENCO, B is the susceptance matrix, Θ is the vector of bus angels, p_G is the vector of bus generation, p_D is the vector of bus loads, p_i^{min} and p_i^{max} are lower and upper generation bounds of i^{th} GENCO, L is number of transmission lines, F_l is power flow in line l and F_l^{min} and F_l^{max} are lower and upper capacity bounds of line l.

4. MARKET POWER

One of the important factors in proposals of participants in power market is their market power which depends on the conditions of participants and their place in the power network. By increasing the market power of each GENCO, it can obtain more benefit by selling more power or by higher prices. There are some indices to measure market power amongst which there are HHI, Lerner, Must Run Ratio, indices [12]. In this article for measuring the market power of GENCOs in the power market, the HHI index is used.

This is a normal index. It determines the market power by measuring the share of generated power by each GENCOs in the power market as follows:

$$
\begin{aligned}
&s_i = \frac{p_i}{\sum_{i=1}^{n_g} p_i} \\
&HHI = \sum_{i=1}^{n_g} s_i^2
\end{aligned} \tag{8}
$$

In which s_i is the share of generation in i^{th} GENCO with respect to the generation of all GENCOs in the power market.

5. Game Theory In Power Market

Competition in the power market is as a game and since ISO clears the proposals of participants simultaneously, we can model the competition in the power market in the simultaneous branch of games in the game theory. To obtain the optimized k for each GENCOs we can use the Nash equilibrium. One of the important factors in biding strategy of GENCOs, is their information about other competitors.

A. Nash Equilibrium

Game in the Nash equilibrium reaches a strategy profile in which the optimized strategy of each player is determined and no player can increase his profit by changing his strategy when the strategy of other players is constant which is obtained in the Nash equilibrium [10]. s*=(s1*,..., sn*) is a strategy profile of Nash equilibrium if the following equation is satisfied:

$$\pi_i\left(s_i^*, s_{-i}^*\right) \geq \pi_i\left(s_i, s_{-i}^*\right) \quad i=1,\ldots,n \qquad (9)$$
$$\forall s_i \in S_i, s_i \neq s_i^*$$

In which π_i is the benefit of i^{th} player, s_i is the strategy of i^{th} player, s_{-i} is the strategy of all players except i^{th} player, S_i is the collection of all decisions of i^{th} player and n is the number of players.

B. GENCO's Competition with Perfect Information

In this model, each GENCO is aware of information like the coefficients of cost function of other competitors and the amount of load in the power network. According to Fig. 1, since the decision of each GENCO is dependent and affective of the decision of other GENCOs, each GENCO can obtain a strategy profile of Nash equilibrium to be able to find its optimized strategy according to the information about other GENCOs.

In fact, we have reached a strategy profile of Nash equilibrium when no GENCO wants to change its k while the k for other GENCOs is constant. To obtain the optimized k for each GENCO, the optimized PSO algorithm was used. According to Fig. 1, in each general iteration, the PSO algorithm runs completely and iterations continue until the Nash equilibrium strategy profile is obtained.

C. GENCO's Competition with Imperfect Information

In today power markets, proposals of each GENCO are confidential for ISO. In this paper, it is assumed that after clearing the power market, the quantity of generated power and the price of power for each GENCO which won can be shown. In the games theory, in the game with imperfect information, because of uncertainty in information about other competitors, each player estimates the decision of other players using the previous information of other players and according to these estimated decisions of other players, decide in the way to maximize his benefit. This benefit is called the expected benefit of that player. After finishing the game, the equality or inequality of the expected benefit with real benefit of each player depends on the accuracy of estimation of that player form the game of the other players. In the game theory in competition with imperfect information, because of estimation of competitor's strategy, Bayesian Nash equilibrium is used. In the power market, according to the above assumption, each GENCO has some information about the price-power curve of other GENCOs in the past hours.

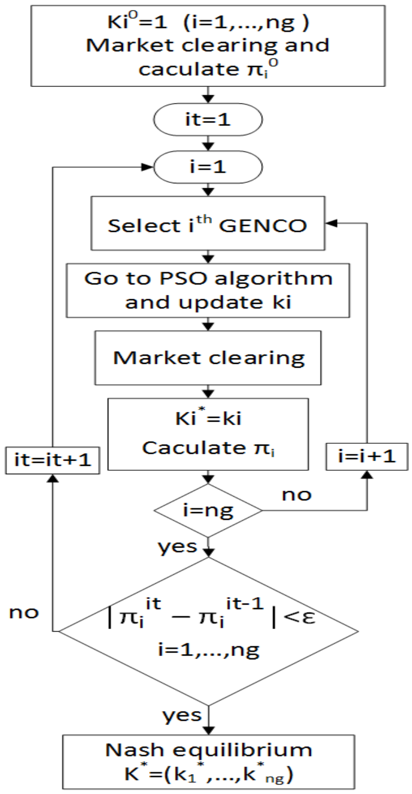

Figure 1: Flowchart of GENCO's competition with perfect information

According to linearity of price-power curve of GENCOs which is shown in equation (3), each GENCO must estimate x and y of the price-power curves of the next hours for each competitor GENCO from x and y of the price-power curves of the previous hours of that competitor to be able to maximize his benefit with the best decision.

According to the Fig. 2, the Monte Carlo experiment with Mt number was used [6]. Such that each GENCO considers two probability functions for each competitor GENCO. One probability function is considered for the estimation of x and one function is considered for the estimation of y of that GENCO.

Since the decision of each GENCO is dependent on decision of other GENCOs, each GENCO must clear the market from ISO stand point to find his optimal strategy as follows:

$$\min \sum_{i=1}^{n_g} \frac{x_i}{2} p_i^2 + y_i p_i \qquad (10)$$

In which x_i and y_i are the coefficients of pricing function of ith GENCO. So each GENCO must estimate x and y of other GENCOs. Now according to the price-power curve of other competitor which was estimated, each GENCO can decide so that it maximizes own benefit.

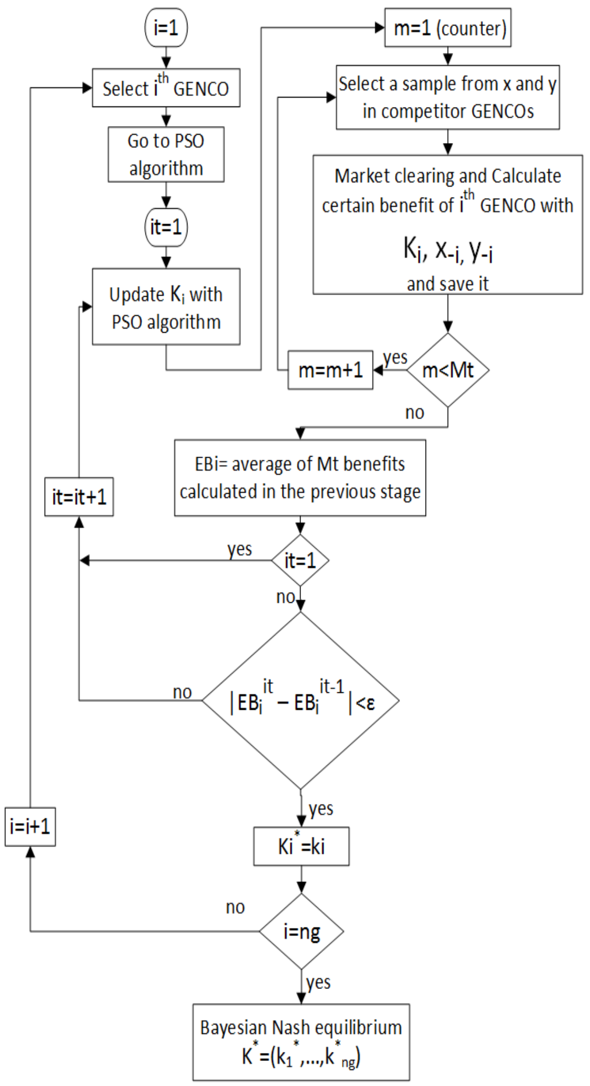

Figure 2: Flowchart of GENCO's competition with imperfect information

Now, to obtain the Bayesian Nash equilibrium, each GENCO by using his own initial k in each time sampling of Monte-Calro, and the estimation of x and y of other competitors, it will calculates his real benefit. Then, it makes a mean from all the benefits calculated in different Monte-Carlo estimation. Consequently, ith GENCO obtains its expected benefit according to its initial k. Afterwards, iterations inside the PSO algorithm will continue until the coefficient k tends to the value that it maximizes the expected benefit of ith GENCO. Then each GENCO will obtain its k to maximize its expected benefit.

6. Numerical Simulation

In this part, 30 bus power network of IEEE is used. 6 existing generators are considered as GENCOs. The amounts of load on different buses are shown in Table 1. GENCOs Bus number and the parameters of GENCOs cost function are shown in Table 2. In simulation of competition with perfect information, initial population and iteration in the PSO algorithm was chosen as 50. In the competition model with imperfect information, required x and y about other competitors were obtained from the first case study in iterations of 5, 6, ..., 15.

According to the type of distribution of x's and y's, to obtain a probable x and y, the normal function as N(μ, σ) was used in the Monte Carlo experiment [14].

Mean and standard deviation values of the normal function of x and the normal function of y for each GENCO is shown in Table 3. The initial population in this model was set as 50 for PSO algorithm and Mt is used at 30.

Table 1
Load on Different Buses

Bus No.	Load(MW)	Bus No.	Load(MW)
2	21.7	17	9
3	2.4	18	3.2
4	7.6	19	9.5
7	22.8	20	2.2
8	30	21	17.5
10	5.8	23	3.2
12	11.2	24	8.7
14	6.2	26	3.5
15	8.2	29	2.4
16	3.5	30	10.6

TABLE 2
BUS NUMBER AND THE PARAMETERS OF COST FUNCTION

GENCO No.	Bus No.	a	b	c
1	1	0.02	2	0
2	2	0.015	1.75	0
3	22	0.023	2.25	0
4	27	0.02	3	0
5	23	0.025	2.5	0
6	13	0.025	2.5	0

TABLE 3
MEAN AND STANDARD DEVIATION VALUES OF THE NORMAL FUNCTIONS

GENCO No.	Parameter	Mean(μ)	Standard deviation(σ)
1	x	0.0288	0.0091
	y	2.9928	0.1146
2	x	0.0295	0.004
	y	3.1219	0.0916
3	x	0.0311	0.0031
	y	3.3187	0.1641
4	x	0.0235	0.0042
	y	3.9852	0.2136
5	x	0.0421	0.0071
	y	3.3792	0.1944
6	x	0.0412	0.0065
	y	3.2415	0.2145

A. *First Case Study*

GENCOs in this case in the model of perfect information, have suggested their own biding strategy. In this case, the capacity of no line of the transmission network is full. This case was convergent after 19 iterations. Simulation results of this case study are shown in Table 4.

TABLE 4
SIMULATION RESULTS OF THE FIRST CASE STUDY

GENCO No.	k	Power (MW)	Price ($/MWh)	Profit ($)
1	1.591	36.45	5.501	58.83
2	1.726	47.89	5.501	85.93
3	1.529	29.32	5.501	45.37
4	1.36	26.09	5.501	33.16
5	1.471	24.78	5.501	36.47
6	1.474	24.64	5.501	36.44
HHI	0.1784			

B. *Second Case Study*

GENCOs competition in this case in the model of perfect information is done. The capacity of transmission line of 1-2 was decreased from 130 MW to 18 MW. In comparison of this state with the first case study, it was deduced that decrease in the capacity of transmission line increased the market power and has increased the price of power in the market and has consequently increased the benefit of GENCOs in the market. In comparison of this case whit first case study, HHI has increased. This case was convergent after 22 iterations. Simulation results of this case study are shown in Table 5.

TABLE 5
SIMULATION RESULTS OF THE SECOND CASE STUDY

GENCO No.	k	Power (MW)	Price ($/MWh)	Profit ($)
1	2.004	28.85	6.354	74.65
2	2.056	44.14	6.356	112.45
3	1.427	45.9	6.198	64.8
4	1.614	22.45	6.308	47.55
5	1.714	23.35	6.3	51.42
6	1.696	24.47	6.348	53.02
HHI	0.1826			

C. *Third Case Study*

This case is when the model with perfect information is done, while the maximum generation of the first GENCO is equal to 20 MW. In comparison of this case with first case study, the first GENCO because of lowering its generation has obtained lower benefit and other GENCOs have more share in the market and obtained more benefit and in general the market power has increased. Increase in price of first GENCO was because increase in market power of other competitors and increase in price of other competitors. In comparison of this case whit first case study, HHI has increased. This case was convergent after 26 iterations. Simulation results of this case study are shown in Table 6.

TABLE 6
SIMULATION RESULTS OF THE THIRD CASE STUDY

GENCO No.	k	Power (MW)	Price ($/MWh)	Profit ($)
1	2.124	18.26	7.003	49.06
2	2.114	52.57	7.001	148.7
3	1.875	32.56	7.001	85.5
4	1.691	28.89	7.001	71.43
5	1.788	28.25	7	71.62
6	1.794	28.48	7.001	72.69
HHI	0.1831			

D. *Forth Case Study*

This case is when the competition is with perfect information whereas the load on bus 2 is 5 MW. In comparison of this case with the first case study, we can see that lowering the load in power network has decrease the market power and has reduced the proposed price of power and lowering the benefit of GENCOs. In comparison of this case whit first case study, HHI has decreased. This case was convergent after 19 iterations. Simulation results of this case study are shown in Table 7.

TABLE 7
SIMULATION RESULTS OF THE FORTH CASE STUDY

GENCO No.	k	Power (MW)	Price ($/MWh)	Profit ($)
1	1.55	34.77	5.196	51.56
2	1.7	38.95	5.196	72.83
3	1.487	27.93	5.196	39.34
4	1.325	24.14	5.196	27.36
5	1.433	23.36	5.196	31.194
6	1.433	23.33	5.196	31.19
HHI	0.1741			

E. Fifth Case Study

This case is when the competition is with imperfect information while the capacity of no line is full. In comparison of this with first case study, we can see that estimation of information about other competitors and their imperfection has changed strategy profile of Nash equilibrium to strategy profile of Bayesian Nash equilibrium and has decreased the market power and during that the benefit of some GENCOs has decreased and some of GENCOs has increased. In fact, decrease in profit of some GENCOs resulted in increase in profit of other GENCOs. Simulation results of this case study are shown in Table 8.

TABLE 8
SIMULATION RESULTS OF THE FIFTH CASE STUDY

GENCO No.	k	Power (MW)	Price ($/MWh)	Profit ($)
1	1.643	34.79	5.568	60.15
2	1.914	38.61	5.568	82.2
3	1.494	31.84	5.551	46.93
4	1.305	31.28	5.546	34.54
5	1.415	27.26	5.467	36.07
6	1.482	25.39	5.589	38.37
HHI	0.1699			

F. Sixth Case Study

This case is when the competition is with imperfect information while the conditions of the second and third case studies have shown separately in Tables 9 and 10, respectively. Present information from past time of the other competitors is related to the first case study. The absence of good information about case studies of second and third resulted in the market power and price of power in the Tables 9 and 10 to be less than case studies of second and third respectively. In fact, the reason why the GENCOs profit in Tables 9 and 10 are less than in Tables 5 and 6 respectively is that uncertainty about strategy of other competitor does not let other GENCOs to obtain maximum profit. Because of lack of precision in historical information, the 3rd GENCO has selected the high biding strategy and 4th GENCO has selected the low biding strategy in Table 9 and this resulted in 3rd GENCO to become expensive and the 4th GENCO to become cheap. In this case the 4th GENCO in Table 9 in comparison to itself in Table 5 sold more power and obtained more profit. In fact decrease in benefit of other GENCOs in Table 9 with respect to Table 5 resulted in increase in profit of 4th GENCO. In comparison of these cases whit fifth case study, HHI has increased.

TABLE 9
SIMULATION RESULTS OF THE SIXTH CASE STUDY

GENCO No.	k	Power (MW)	Price ($/MWh)	Profit ($)
1	1.857	31.95	5.997	72.28
2	2.021	42.08	5.997	102.3
3	1.52	30.34	5.997	59.92
4	1.342	38.35	5.997	49.52
5	1.659	23.38	5.997	47.55
6	1.666	23.08	5.997	47.32
HHI	0.1750			

TABLE 10
SIMULATION RESULTS OF THE SIXTH CASE STUDY

GENCO No.	k	Power (MW)	Price ($/MWh)	Profit ($)
1	1.894	20	6.531	42.91
2	2.103	45.23	6.532	121.18
3	1.634	38	6.532	75.32
4	1.546	30.62	6.532	60.47
5	1.701	26.79	6.532	59.6
6	1.663	28.54	6.532	60.9
HHI	0.1777			

G. Seventh Case Study

This case is when the competition is with imperfect information in which imperfect estimation of the third GENCO from other GENCOs has decreased his benefit and increased the benefit of the other competitors. The third GENCO has overestimated the mean of x of the other competitors by 0.01 and the mean of y of other competitor by 0.5. False information of 3rd GENCO about other competitors caused more market power of other GENCOs. In comparison of this case whit fifth case study, HHI has increased. Simulation results of this case study are shown in Table 11.

TABLE 11
SIMULATION RESULTS OF THE SEVENTH CASE STUDY

GENCO No.	k	Power (MW)	Price ($/MWh)	Profit ($)
1	1.641	37.92	5.772	67.09
2	1.914	42.19	5.772	91.89
3	1.924	16.04	5.75	38.84
4	1.305	35.08	5.743	39.55
5	1.415	29.69	5.639	40.02
6	1.482	28.25	5.799	43.68
HHI	0.1784			

7. CONCLUSION

In this paper, in the two models of competition with perfect and imperfect information, the biding strategy of GENCOs was done. In both of two models, the PSO algorithm was used for the optimization. In the model of competition with imperfect information, a method for using the previous information and estimation of required information has suggested. In this method, the linear curve of price-power in the previous hours was sampled and the curve of price-power in the next hour for each GENCO was estimated. Then it was shown in the numerical simulation that lowering the load and not good information has decreased the market power and has filled the capacity of transmission line and lowering the market share of each GENCO has increased the market power.

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