Impact of Participants' Market Power and Transmission Constraints on GenCos' Nash Equilibrium Point

A. Badri*, S. Jadid* and M. Parsa-Moghaddam**

Abstract: Unlike perfect competitive markets, in oligopoly electricity markets due to strategic producers and transmission constraints GenCos may increase their own profit through strategic biddings. This paper investigates the problem of developing optimal bidding strategies of GenCos considering participants' market power and transmission constraints. The problem is modeled as a bi-level optimization that at the first level each GenCo maximizes its payoff through strategic bidding and at the second level, in order to consider transmission constraints a system dispatch is accomplished through an OPF problem. The AC power flow model is used for proposed OPF. Here it is assumed that each GenCo uses linear supply function model for its bidding and has information about initial bidding of other competitors. The impact of optimal biddings on market characteristics as well as GenCos' payoffs are investigated and compared with perfect competitive markets where all the participants bid with their marginal costs. Furthermore, effects of exercising market power due to transmission constraints as well as different biddings of strategic generators on GenCos' optimal bidding strategies are presented. Finally IEEE-30 bus test system is used for case study to demonstrate simulation results.

Keywords: Bidding Strategy, Market Power, Nash Equilibrium, Oligopoly Market, Transmission Constraints.

1 Introduction

In deregulated electricity markets GenCos are facing a new established problem entitled, optimal bidding strategy, to benefit more from bidding to the centralized spot market. All researches carried out in this area can be divided in two main categories, one those employing game theory for bidding strategy and the rest which use stochastic methodologies. The first group uses game theory to reach the Nash equilibrium for GenCos. There are two types of games regarding GenCos' policy in their bidding strategies, non-cooperative and cooperative games. In [1] a non-cooperative market is modeled and a Cournot game is solved to simulate oligopoly market equilibrium. A non-cooperative game with incomplete information is employed in [2] that uses discrete bids for bidding strategies, however no constraint is taken into account. A transmission constrained bidding strategy with incomplete information is conducted in [3, 4] that uses bi-level optimization with DC optimal power flow. In [5] a model is presented for bidding strategies with incomplete information in which each supplier bids part of its energy and self schedules the rest. The model considers a full competitive market that is unrealistic. In [6] a stochastic optimization model is used to develop optimal bidding strategies of GenCos, considering transmission congestion, however participants' market power is not taken into account. Conejo and et al presented a framework to obtain bidding strategy of price taker producers by estimating probability density function of market clearing price, regardless of impact of network constraints [7]. Fuzzy-c-mean and artificial neural networks are employed to develop bidding strategies of GenCos in a perfect competition market without network considerations [8]. In [9] the problem of building optimally coordinated bidding strategies for competitive suppliers in energy and spinning reserve markets is addressed. An imperfect market with uniform price is considered in [9] that transmission network is not taken into account. Finally a detailed literature review of bidding strategies in electricity market is presented in [10].

In this paper the problem of developing optimal bidding strategies of GenCos in an imperfect competition, oligopoly electricity market is presented that GenCos' market power and transmission constraints are taken into consideration. The linear supply function model is

* A. Badri and S. Jadid are with the Center of Excellence for Power System Automation and Operation, Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran.
E-mails: a_badri73@yahoo.com, jadid@iust.ac.ir.
** M. Parsa-Moghaddam is with the Department of Electrical Engineering, Tarbiat Modares University, Tehran, Iran.
E-mail: parsa@modares.ac.ir.

considered for bidding strategy of proposed market that enables suppliers to bid simultaneously both their prices and quantities as well. The problem is formulated as a two-level optimization in which first level maximizes GenCos' payoff and second level deals with market clearing from ISO point of view that considers ancillary services such as reactive power, system voltage as well. The Primal Dual Interior Point Method (PDIPM) is applied for solving market clearing OPF. Finally GenCos' optimal bidding strategies are derived based on OPF sensitivity function to reach the Nash equilibrium.

It is assumed that there is a complete information market and an AC power flow model is used for proposed OPF. The impact of exercising market power due to transmission constraints as well as biddings of strategic generators is investigated and compared with the perfect competitive markets where all the participants bid with their marginal costs.

The paper is organized as follows: The formulation of proposed OPF and bidding strategy problems are given in Section 2 and the solution strategy is presented in Section 3. Section 4 illustrates numerical results using IEEE-30 bus test system and finally Section 5 provides the conclusions.

2 Formulation

Assuming that a_i, b_i, c_i are marginal cost coefficients of generator i, operation cost function of this unit will be as Eq. (1):

$$C_{gi} = a_i . P_{gi}^{2} + b_i . P_{gi} + c_i \qquad (1)$$

In an oligopoly market with imperfect competition each generator is capable to bid not necessarily with its marginal cost. In this case suppose that generator i bids as:

$$C_{gi} = k_i . P_{gi}^{2} + b_i . P_{gi} + c_i \qquad (2)$$

where k_i is the bidding multiplier ($k_i \geq a_i$) that in a special case would be optimal bidding strategy of unit i . Assuming there is complete information and each GenCo has information about initial biddings offered by other competitors, the problem formulation is divided into two sub-problems dealing with system dispatch and GenCos optimal biddings as follows.

2.1 System Dispatch Problem

For an optimal bidding, GenCos should consider transmission constraints while bidding to the market. For this purpose each GenCo, knowing biddings of other competitors, should solve a dispatch problem using OPF. Considering Eq. (2) the OPF problem can be formulated as Eq. (3) where the objective function is

minimizing the system cost and all transmission constraints are taken into account.

$$\text{Min} \quad \sum_{i=1}^{m} k_i . P_{gi}^{2} + b_i . P_{gi} + c_i$$

$$P_{gi} - P_{di} = \sum_{j=1}^{n} V_i V_j |Y_{ij}| \cos(\theta_i - \theta_j - \alpha_{ij})$$

$$Q_{gi} - Q_{di} = \sum_{j=1}^{n} V_i V_j |Y_{ij}| \sin(\theta_i - \theta_j - \alpha_{ij}) \qquad (3)$$

$$P_{gi\,min} \leq P_{gi} \leq P_{gi\,max}$$

$$Q_{gi\,min} \leq Q_{gi} \leq Q_{gi\,max}$$

$$V_{i\,min} \leq V_i \leq V_{i\,max}$$

$$P_{lim\,in} \leq P_{li} \leq P_{lim\,ax}$$

where
P_{gi}, Q_{gi} : Active and reactive powers of unit i
P_{di}, Q_{di} : Active and reactive power consumption of consumer i
P_{li} : Power flowing from line i
m, n : Number of generators and buses
α_{ij} : Angle of ijth element of admittance matrix
$|Y_{ij}|$: Magnitude of ijth element of admittance matrix
V_i, θ_i : Voltage magnitude and angle of bus i

2.2 Optimal Bidding Strategy

Besides satisfying network constraints, GenCos are looking for optimal biddings in order to maximize their payoff as shown in Eq. (4)

$$\text{Max} \quad R_i = \sum_{j=1}^{n_i} [\lambda_j . P_{gj} - (a_j . P_{gj}^{2} + b_j . P_{gj} + c_j)] =$$
$$\lambda_{Gencoi}^{T} . P_{Gencoi} - (P_{Gencoi}^{T} . A_i . P_{Gencoi} + B_i^{T} . P_{Gencoi} + C_i) \qquad (4)$$

In which:
λ_j : Nodal price of bus j
λ_{Gencoi} : Vector of GenCo i nodal prices
P_{Gencoi} : Vector of GenCo i generation outputs
A_i, B_i, C_i : Vectors of GenCo i operation cost coefficients
n_i : Number of generators located in GenCo i

Combining Eqs. (3) and (4) complete optimal bidding problem is derived that satisfies transmission constraints.

$$\text{Max} \quad R_i$$
$$\text{Subject to : OPF problem} \qquad (5)$$

In above bidding problem, it is assumed that generators just bid with their a_i coefficient, while b_i and c_i are constant. Furthermore as it is clear generator's bidding coefficient k_i does not appear in their maximum payoff function, although R_i is an implicit function of k_i, through λ_i and P_{gi}, where λ_i and P_{gi} for each generator are determined by the OPF.

3 Solution Strategy

In order to solve this problem, at first OPF sub problem should be solved to determine variables required in main optimality objective function. The bidding model presented in this framework is based on Interior Point OPF model for which a nonlinear PDIPM [11] is directly applied to OPF. The general procedure of an IPM method, which is employed in an OPF model, is as presented in Eq. (6)

$$\text{Min } f(t)$$
$$\text{Subject to : } p(t) = 0 \qquad (6)$$
$$q_l \le q(t) \le q_u$$

One of the main advantages of IPM is its capability to deal with inequality constraints. According to PDIPM optimization method, slack variables (s_l, s_u) are used to transform inequality constraints into equality constraints in which slack variables are incorporated by barrier parameter (μ). Therefore lagrangian function can be formed as:

$$\text{Min } L = f(t) - \lambda^T p(t) + \gamma_l^T (q(t) - s_l - q_l)$$
$$+ \gamma_u^T (q(t) + s_u - q_u) - \mu(\sum_{i=1}^{ne} \ln s_{li} + \sum_{i=1}^{ne} \ln s_{ui}) \qquad (7)$$
$$s_l \ge 0, \ s_u \ge 0, \ \gamma_l < 0, \ \gamma_u > 0, \ \mu > 0$$

Here :
t : Set of primal variables, containing all equality and inequality constraint Variables (P_{gi}, V_i, θ_i)
λ: Vector of lagrangian coefficients
γ_l, γ_u : Vector of dual variables
ne : Number of inequality constraints

Applying first order optimally condition and using Newton method, reduced form of Karush-Kahn-Tucker (KKT) equations will be as follows [11]:

$$A.\Delta T = R \qquad (8)$$

In which:

$$A = \begin{bmatrix} -H_l(t,\lambda) & J^T(t) \\ J(t) & 0 \end{bmatrix} \qquad (9)$$

$$\Delta T = [\Delta t \quad \Delta \lambda]^T \qquad (10)$$

$$R = [r \quad -p(t)]^T \qquad (11)$$

$$H_l(t,\lambda) = \frac{\partial q^T}{\partial t}([s_u]^{-1}[\gamma_u] - [s_l]^{-1}[\gamma_l]) \frac{\partial q}{\partial t} + H(t,\lambda) \qquad (12)$$

$$r = \frac{\partial f(t)}{\partial t} - J^T(t)\lambda + \frac{\partial q^T}{\partial t}([s_u]^{-1} - [s_l]^{-1})\mu e \qquad (13)$$

In above equations $H(t,\lambda)$ is Hessian matrix of lagrangian function [11] and e is unity vector and J is Jacobian matrix. In order to obtain optimal bidding strategies, applying first-order derivative with respect to K to Eq. (8) (due to $\Delta t = 0$ at optimal solution) we have:

$$\frac{\partial T}{\partial K} = A^{-1} . \frac{\partial R}{\partial K} \qquad (14)$$

where:

$$\frac{\partial T}{\partial K} = [......, \frac{\partial P_{gi}}{\partial k_i}, \frac{\partial V_i}{\partial k_i}, \frac{\partial \theta_i}{\partial k_i}, \frac{\partial \lambda_i}{\partial k_i}, ...] \qquad (15)$$

where K is vector of bidding strategies.
Similarly applying second-order derivative to Eq. (8) and considering the same constraints we have:

$$\frac{\partial^2 T}{\partial K^2} = 2.A^{-1}.\frac{\partial A}{\partial K}.\frac{\partial T}{\partial K} \qquad (16)$$

Similarly it is second order derivatives of primal and dual variables as shown in Eq. (17).

$$\frac{\partial^2 T}{\partial K^2} = [......, \frac{\partial^2 P_{gi}}{\partial k_i^2}, \frac{\partial^2 V_i}{\partial k_i^2}, \frac{\partial^2 \theta_i}{\partial k_i^2}, \frac{\partial^2 \lambda_i}{\partial k_i^2}, ...] \qquad (17)$$

In order to determine and update bidding coefficients of generators, applying first-order optimally conditions to Eq. (4) and using Newton method [12] we have:

$$\frac{\partial^2 R_i}{\partial K_i^2}\Big|_{K_{i\,old}} . \Delta K_i = -\frac{\partial R_i}{\partial K_i}\Big|_{K_{i\,old}} \qquad (18)$$

$$K_{i\,new} = K_{i\,old} - \frac{(\frac{\partial R_i}{\partial K_i}\Big|_{K_{iold}})}{(\frac{\partial^2 R_i}{\partial K_i^2}\Big|_{K_{i\,old}})} \qquad (19)$$

where K_i is vector of bidding strategies of GenCo i.
First-order and second-order derivatives of R_i with respect to K_i are:

$$\frac{\partial R_i}{\partial K_i} = (\lambda_{Gencoi}^T - B_i^T - 2.P_{Gencoi}^T.A_i).\frac{\partial P_{Gencoi}}{\partial K_i}$$
$$+[\frac{\partial \lambda_{Gencoi}}{\partial K_i}]^T.P_{Gencoi} \qquad (20)$$

$$\frac{\partial^2 R_i}{\partial K_i^2} = 2([\frac{\partial \lambda_{Gencoi}}{\partial K_i}]^T - [\frac{\partial P_{Gencoi}}{\partial K_i}]^T.A_i).\frac{\partial P_{Gencoi}}{\partial K_i}$$
$$+(\lambda_{Gencoi}^T - B_i^T - 2.A_i.P_{Gencoi}^T).\frac{\partial^2 P_{Gencoi}}{\partial K_i^2} + \qquad (21)$$

$$[\frac{\partial^2 \lambda_{Gencoi}}{\partial K_i^2}]^T.P_{Gencoi}$$

In which first order and second order derivatives of P_{Gencoi} and λ_{Gencoi} in Eqs. (20) and (21) are obtained through Eq. (15) and (17), respectively. Deriving expressions in (20) and (21), optimal bidding strategy of each generator is determined and updated through Eq. (19). If we take GenCo i into account, assuming other generators' bidding strategies are known, a game process is accomplished to update corresponding biddings. This process can be repeated for all other GenCos. Each GenCo can update its bidding by initial bidding strategies of other competitors. The process stops when none of units would like to change its bids.

Note that in a power system with transmission constraints taken into account, game may result in Nash equilibrium or multiple [13] or no equilibrium at all (due to market power).

4 Simulation Results

An IEEE-30 bus test system is employed to illustrate simulation result. It is assumed that there are six GenCos each containing one unit, competing with each other. The information on generators and loads are shown in Tables 1 and 2, respectively. Transmission network is given in [14].

Table 1 Generators' data.

Generator buses	a	b	c	P_{imax}	P_{imin}
1	0.02	2	0	180	0
2	0.175	1.75	0	180	0
3	0.625	1	0	150	0
4	0.0834	3.25	0	150	0
5	0.25	3	0	130	0
6	0.25	3	0	140	0

Table 2 Load data.

Bus	P_d(Mw)	Bus	P_d(Mw)
2	35.7	18	3.2
5	3.2	19	9.5
7	22.8	20	2.2
8	30	21	17.5
10	5.8	22	2.4
12	11.2	24	8.7
14	6.2	26	3.5
15	8.2	27	7.6
16	3.5	29	2.4
17	9	30	10.6

In order to show the accuracy of proposed bidding strategy, Fig.1 illustrates initial biddings and optimal bidding strategies of each generator, assuming other competing generators bid with their initial bidding coefficients. As it is appear all generators have increased their initial biddings to reach the corresponding Nash equilibrium point. Here it is assumed that each GenCo obtains its optimal bidding, given that the others bid at their initial costs. This process can be repeated if each GenCo changes its bidding. Consequently, Fig. 2 shows corresponding payoffs of existing GenCos in two mentioned cases, respectively. Comparing different payoffs in Fig. 2, it is clear that in Nash equilibrium point each GenCo has increased its payoff in comparison with marginal biddings. It is due to existing fix loads which must be satisfied in all period of times. Therefore, bidding with the prices higher than true initial costs results in higher prices and consequently increases in GenCos' corresponding payoffs.

In game theory the players are mutually interdependent and the situation of each player directly affects the final decision of other players. Nevertheless, a non-cooperative game can be static game or dynamic game. In a static game the players make their moves in isolation, without knowing what other players have done. However, in a dynamic game that is more realistic and more accurate the players make their own decisions based on the strategies given by others rivals. A dynamic game results in Nash equilibrium that is the best (most profitable) strategy for all players. Nash equilibrium is interpreted as the optimal response of each player to a given set of strategies chosen by other players. Therefore, knowing (or estimating) other rivals' strategies is necessary to obtain Nash equilibrium point.

In our study in order to show the impact of initial values on optimal bidding strategies, Table 3, illustrates GenCo1's optimal bidding strategies and corresponding payoffs when this GenCo bids with different estimation of other rivals' strategies. As shown, maximum profit is obtained when GenCo 1 has the correct estimation of its rivals' (true) marginal costs.
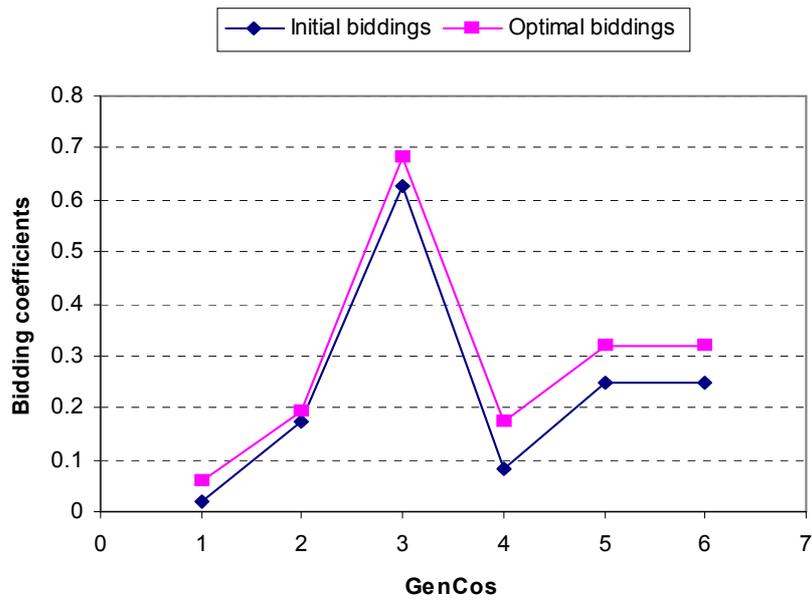
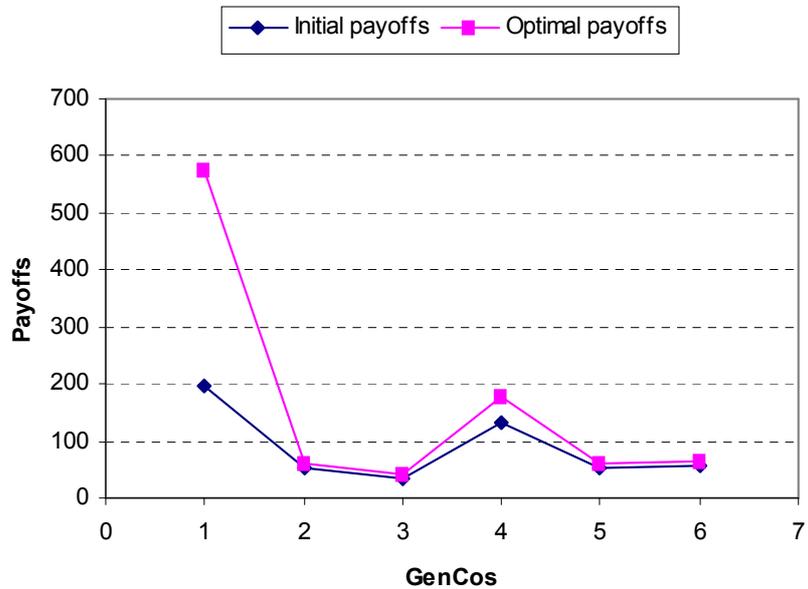**Fig. 1** Comparison of GenCos' initial and optimal bidding strategies.

Fig. 2 Comparison of GenCos' initial and optimal payoffs.

Table 3 Gencos 1' payoffs with respect to different estimation of rivals' behaviors.

Case	Estimation of rivals' strategies	Optimal bidding strategy of GenCo1	GenCo Payoff
1	0.76*(True marginal costs)	0.0502	564.37
2	0.83*(True marginal costs)	0.0524	568.83
3	0.91*(True marginal costs)	0.0565	573.12
4	1.0*(True marginal costs)	0.0586	573.56
5	1.10*(True marginal costs)	0.0615	572.32
6	1.20*(True marginal costs)	0.0650	568.59
7	1.30*(True marginal costs)	0.0685	562.79

Note that with a given set of strategies (proposed by the rivals) the optimal bidding strategy of each GenCo is the same, regardless of its initial values. In the other words, the optimal bidding strategy of each player depends on the others initial bids. However, it is independent of its initial bidding values. Table 4 illustrates generators' nodal prices as well as corresponding payoffs when, simultaneously all GenCos bid with their initial and optimal bidding coefficients. As shown the nodal prices of all participants have gone up due to their increase in initial biddings. Furthermore as expected from optimal bidding strategy procedure, all GenCos' payoffs have been increased due to their market power to change their biddings and market prices as well. Consequently, generators' corresponding output powers in these two above situations are depicted in Fig. 3. As shown in this figure, outputs of generators 1 and 4 are reduced. This is because they are initially cheap units and bidding with prices much higher than their marginal costs causes reduction in their output powers, however outputs of

other generators are increased, due to increasing rates of corresponding bidding coefficients.

Table 4 Generators' nodal prices and payoffs.

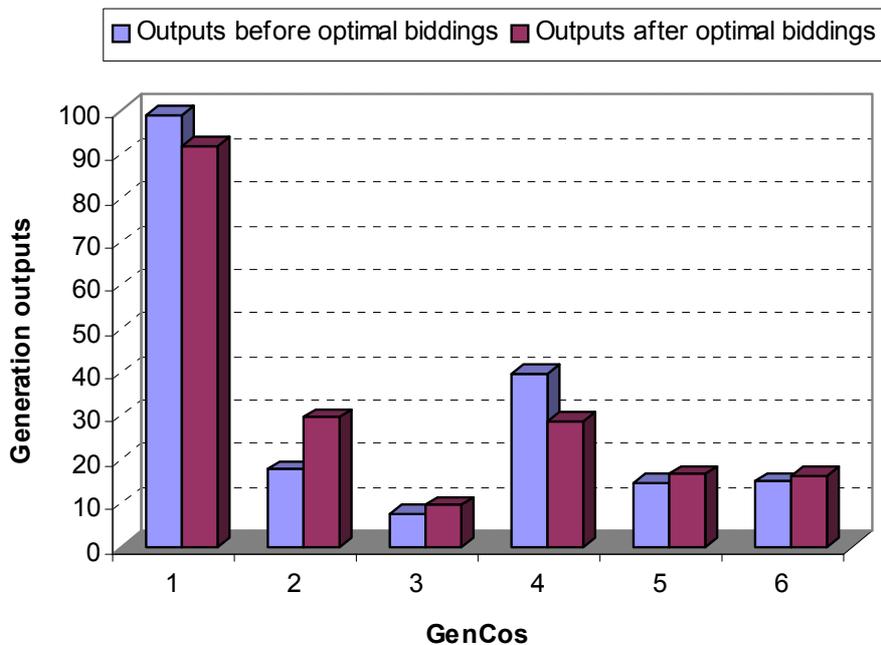| GenCo	Before Nash equilibrium point		After Nash equilibrium point	
	λ_i	Payoff	λ_i	Payoff
1	5.957	195.74	12.784	822.81
2	7.925	54.471	13.131	183.57
3	10.392	35.28	13.758	64.662
4	9.867	131.23	13.351	222.35
5	10.309	53.423	13.52	105.45
6	10.423	55.096	13.547	105.8

Fig. 3 Comparison of GenCos' outputs before and after Nash equilibrium when all bid strategically.

In imperfect competitive markets such as oligopoly markets, each of the participants may be able to exercise its market power through optimal bids. In these cases, transmission constraints play an important role to form market characteristics and participants' final payoffs. In another words, in spite of perfect competitive markets, in which all the participants must bid with their marginal costs, here each GenCo considering transmission characteristics is capable to bid higher than its marginal cost to benefit the market. In order to show the impact of GenCos optimal biddings, Table 5

illustrates the comparison of GenCos' output powers as well as their corresponding profits in two cases, with perfect competitive market and no transmission constraints and imperfect competitive market and transmission constraints, respectively. As shown exercising market power in the imperfect competitive markets, results in higher nodal prices and higher respective profits as well. Furthermore, in comparison to Table 4 it is appear that, while GenCos bid with their initial (marginal) costs, transmission constraints may affect the participants' final payoffs.

Table 5 Generation outputs, nodal prices and payoffs.

GenCo	Perfect competition with no transmission constraints			Imperfect competition with transmission constraints		
	λ_i	P_{gi}	Payoff	λ_i	P_{gi}	Payoff
1	7.261	131.6	346	12.784	91.99	822.81
2	7.261	15.18	43.2	13.131	29.63	183.57
3	7.261	5.01	15.7	13.758	9.36	64.662
4	7.261	24.1	49	13.351	28.91	222.35
5	7.261	8.52	18.3	13.520	16.47	105.45
6	7.261	8.52	18.3	13.547	16.43	105.8

As mentioned in an optimal bidding strategy, generators might bid either based on competitors' initial biddings or their new updated bidding strategies. Table 6 shows optimal bidding strategies and corresponding payoffs of the generators in two different cases, that in the first case each generator updates its bidding according to initial bidding strategies of other competitors, while in the second case each generator uses new updated bidding strategies of other competitors to achieve to its optimal bidding strategy. As illustrated according to type of strategy that will be selected, optimal bidding strategies as well as corresponding payoffs are different. However in the second case GenCos' payoffs are decreased due to response to new updated bidding strategies of other competitors.

The impact of transmission capacity constraints on optimal bidding strategy and other specifications of GenCos is shown in Table 7. To clarify the impact of network constraints, here it is assumed that load in each bus is stressed with 1.33 times its initial value (shown in Table 2). In this case transmission lines 4, 30 and 33 are congested. According to Table 7 when transmission constraints are taken into account nodal prices are much higher than those in an unconstrained system. Furthermore as shown GenCos 2-6 will benefit more because of exercising their market power due to transmission constraints, while GenCo1 will earn less because of its lower generation in this case.

Table 6 Optimal bidding strategies and corresponding payoffs in two cases.

Genco	Case1		Case2	
	Optimal bidding	Payoff	Optimal bidding	Payoff
1	0.05861	822.81	0.05857	739.73
2	0.19207	183.57	0.20466	160.49
3	0.68130	64.662	0.65840	56.941
4	0.17468	222.35	0.12572	225.07
5	0.31926	105.45	0.29295	92.113
6	0.32098	105.8	0.28656	93.396

Table 7 Gencos' characteristics with transmission constraints and load stress.

Unconstrained transmission			Constrained transmission		
k_i	λ_i	Payoff	k_i	λ_i	Payoff
0.05908	14.869	1164.3	0.083725	16.416	1092.8
0.19061	15.237	258.09	0.20279	23.257	648.37
0.64563	16.024	90.195	0.77277	32.123	373.29
0.10759	15.098	399.51	0.18924	24.988	973.45
0.27539	15.688	157.04	0.4565	25.736	411.16
0.26912	15.84	160.17	1.0304	34.65	427.13

Unlike, perfect competition markets that all units are urged to bid with maximum capacity at their marginal costs, in an imperfect oligopoly market there is no guarantee that GenCos bid with their maximum capacity. In other words, in this markets GenCos (specially those containing cheap units) might exercise market power and bid not necessarily with their maximum capacity, in order to cause nodal prices go up and increase their payoff. To illustrate the impact of binding maximum capacity on optimal bidding strategies of GenCos, Table 8 shows GenCos' characteristics when GenCo1 fixes its maximum power to 80 MW. Comparing Tables 4 and 8 it is clear that since generator 1 is a cheap unit, exercising market power for not bidding its full capacity in the market, causes increases in nodal prices. The reason is that since GenCo 1 has limited its maximum outputs, nodal prices are determined by some other units that are more expensive and accordingly, corresponding profit is increased. Furthermore, it appears that other competitors will benefit from exercising market power via GenCo1. Considering generation output powers, we see the output of generator 1 is bounded to 80 MW while generation outputs of units 3-6 are increased to meet the load demand.

To illustrate the impact of fixing GenCos' maximum capacity on optimal bidding strategies and Nash equilibrium, Fig. 4 shows GenCos initial biddings with respect to their optimal bidding strategies when GenCo1 withholds its generation on 80 MW.

Table 8 Gencos' characteristics when generator 1 fixes its generation output.

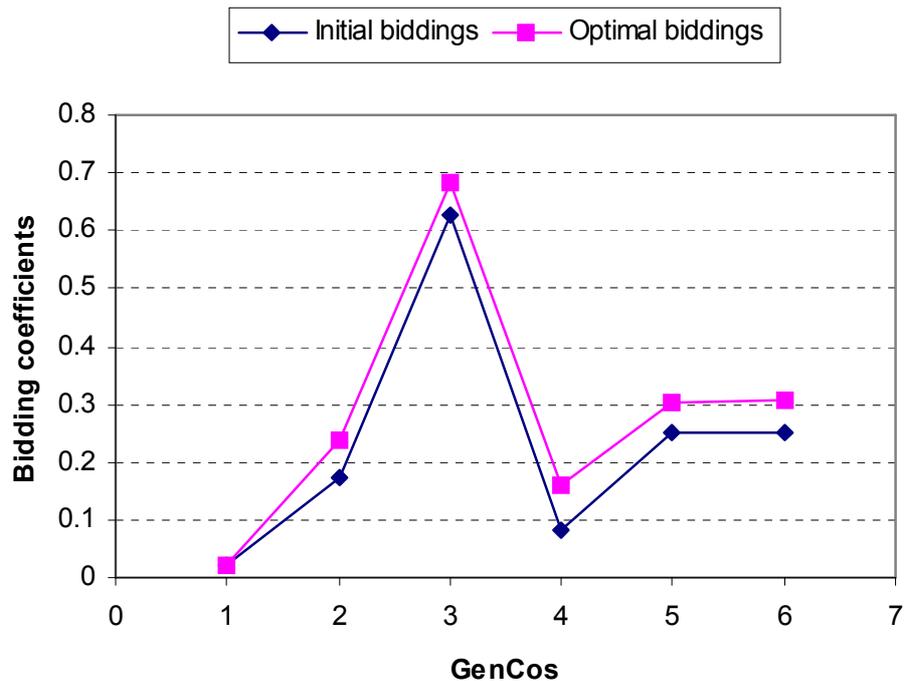| Genco	k_i	λ_i	P_{gi}	Payoff
1	0.02	14.474	80	869.9
2	0.2367	14.733	26.82	222.35
3	0.6853	15.264	10.57	80.933
4	0.1586	14.708	36.44	306.79
5	0.3025	14.920	19.21	136.73
6	0.3084	14.028	19.34	139.11

Fig. 4 Comparison of GenCos' bidding strategies when GenCo 1 fixes its generation with the respective true marginal costs.

In this case, GenCo 1 bids with its marginal cost, however all other GenCos have increased their initial bids to reach the higher payoffs. It should be noted that here the game results in multiple Nash equilibrium for GenCo 1 ($0.02 \leq k_1 \leq 0.042$) that all provide the same (maximum) profit for it

5 Conclusion

In this paper optimal bidding strategy of GenCos is modeled that considers participants' market power and transmission constraints. Supply function equilibrium is employed to model GenCos' bidding strategies in an oligopolistic market. The problem is modeled with a bi-level optimization that uses PDIPM to solve. Main advantages of IPM are found as its fast convergence and capabilities to reduce problem scale and model inequality constraints. It is shown that due to optimal biddings, system nodal prices as well as GenCos' profits are increased in comparison to perfect competitive market that all the suppliers bid with their marginal costs. Optimal bidding strategies may be implemented via two manners, using competitors' initial cost functions or their new updated cost functions, respectively. Impacts of system characteristics and GenCos' payoffs in each case is obtained and compared. It is illustrated that exercising market power due to transmission constraints as well as generation bindings, causes increases in nodal prices, that in former case some participants are able to benefit from deduced high nodal prices, due to their characteristics and strategic locations, while in latter case all participants may be able to benefit from generation binding of some cheap and strategic units.

References

[1] Wen F. S. and David A. K, "Oligopoly electricity market production under incomplete information," *IEEE Power Eng. Rev.*, Vol. 21, No. 2, pp. 58-61, Apr. 2001.

[2] Ferrero R., Rivera J., and Shahidehpour M., "Applications of games with incomplete information for pricing electricity in deregulated power pools," *IEEE Trans. Power Syst.*, Vol. 13, No. 2, pp. 184-189, Feb. 1998.

[3] Li T. and Shahidehpour M., "Strategic bidding of transmission-constrained GENCOs with incomplete information," *IEEE Trans. Power Syst.*, Vol. 20, No. 2, pp. 437-447, Feb. 2005.

[4] Gountis V. P. and Bakirtzis A. G., "Bidding strategies for electricity producers in a competitive electricity market place," *IEEE Trans. Power Syst.*, Vol. 19, No. 5, pp. 356-365, Feb. 2004.

[5] Zhang D., Wang Y., and Luh P. B., "Optimization based bidding strategies in the deregulated market," *IEEE Trans. Power Syst.*, Vol. 15, No. 2, pp. 981-986, Aug. 2000.

[6] Ma L., Wen F., Ni Y., and Wu F. F., "Optimal bidding strategies for generation companies in electricity markets with transmission capacity constraints taken into account," *in Proc. IEEE/PES Summer Meeting*, Vol. 2, No. 7, pp. 2604-2610, Jul. 2003.

[7] Conejo A. J., Nogales F. J., Arroyo J. M., "Price taker bidding strategy under price uncertainty," *IEEE Trans. Power Syst.*, Vol. 17, No. 5, pp. 1081-1088, Nov. 2002.

[8] Hong Y. Y., Tsai S. W, and Weng M. T., "Bidding strategy based on artificial intelligence for a competitive electric market," *IEE Proc.-Gener. Transm. Distrib.*, Vol. 148, No. 2, pp.159-163, March. 2001.

[9] Wen F. S. and David A. K., "Optimally co-ordinated bidding strategies in energy and ancillary service markets," *IEE Proc.-Gener. Transm. Distrib.*, Vol. 149, No. 4, pp. 331-338, May. 2002.

[10] David A. K. and Wen F., "Strategic bidding in competitive electricity market: A literature survey," *in Proc. IEEE Power Eng. Soc. Power Eng. Conf.*, Vol. 2, No. 2, pp. 2168-2173, Jun. 2000.

[11] Jabr R. A., A primal-dual interior point method to solve the optimal power flow dispatching problem, *Springer Optimization and Engineering J.* Vol. 4, No. 2, pp. 309-336, Nov 2004.

[12] Weber J. and Overbye T., "A two-level optimization problem for analysis of market bidding strategies," *in Proc. IEEE/PES Summer Meeting*, Vol. 2, No. 5, pp. 682-687, Jul. 1999.

[13] Baldick R., "Electricity market equilibrium models: the effect of parameterization," *IEEE Trans. Power Syst.*, Vol. 17, No. 4, pp. 1170-1176, Nov. 2002.

[14] Saadat H., *Power System Analysis*, WCB Mc Graw Hill Companies, New York, 1999.
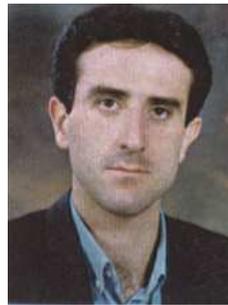
Ali Badri was born in Iran, on 1973. He received the B.Sc. degree in electrical engineering from Isfahan University of Technology in 1995 and the M.Sc. degree from the Iran University of Science and Technology, Tehran, in 2000. He is currently a Ph.D. student in the Department of Electrical Engineering, Iran University of Science and Technology. His research interests are restructured power systems, FACTS, and power quality and harmonics.

Shahram Jadid received the Ph.D. degree in1991 from the Indian Institute of Technology, Bombay, India. He is an Associate Professor in the Department of Electrical Engineering, Iran University of Science and Technology, Tehran, where he is also currently Head of the Center of Excellence for Power Systems Automation and Operation. His main research interests are power system operation and restructuring, load and energy management.

Mohsen Parsa-Moghaddam was born in Iran, on 1956. He received the B.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1980, the M.Sc. degree from the Toyohashi University of Technology, Japan, in 1985, and the Ph.D. degree from Tohoku University, Japan, in 1988.

Currently, he is an Associate Professor in the Department of the Electrical Engineering, Tarbiat Modares University, Tehran, Iran. His research interests include power system planning & control, optimization, and restructuring.