http://jecei.srttu.edu

SRTTU

Journal of Electrical and Computer Engineering Innovations

JECEI, Vol. 4, No. 1, 2016

Regular Paper

# A Comprehensive Survey on GenCos' Optimal Bidding Strategy Problem in Competitive Power Markets

**Ali Badri**[1,*]

[1] Faculty of Electrical Engineering Shahid Rajaee Teacher Training University (SRTTU), Lavizan, 16788-15811, Tehran, Iran.

[*]Corresponding Author's Information: ali.badri@srttu.edu

**ARTICLE INFO**

**ARTICLE HISTORY:**
Received 15 February 2016
Revised 28 March 2016
Accepted 28 March 2016

**KEYWORDS:**
Generation company
Optimal bidding strategy
Uncertainty
Price

**ABSTRACT**

This paper represents a complete survey on Generation Companies' (GenCos') optimal bidding strategy problem in restructured power markets. In this regard after an introduction to competitive electricity markets, concept of optimal bidding strategy is presented. Considering large amount of works accomplished in this area a novel classification is implemented in order to categorize the existing diverse studies. Accordingly, studies are classified in different categories based on market mechanism, trading mechanism, type of competition, transmission security, type of power plant, type of commodity and type of objective function. For each category, the corresponding studies are presented to show the effectiveness of each item. At the end, the impact of uncertainty and risk on GenCos' optimal bidding strategy problem is represented and a number of applicable methods to simulate stochastic nature of the problem are investigated. The presented paper may be applicable for that group of researches that are interested in GenCos' optimal bidding strategy to give a comprehensive perspective in this issue.

## 1. Introduction

The worldwide electricity industry had experienced a movement towards new established markets based upon a competitive environment. These new electric markets enable the customers to buy their necessary power from different GenCos in order to reduce their costs. Two widely known markets so-called pool and bilateral markets are employed in deregulated power markets. The former is a centralized market where both sellers and buyers simultaneously participate in it, while the latter is based on direct transactions between GenCos/marketers and consumers through pre-determined bilateral agreements. The main challenges that GenCos are dealing with in a centralized pool-based market is managing the optimal bidding strategies.

In a centralized pool market, participants may bid directly with their linear cost functions by changing corresponding characteristics or they may bid with their nonlinear cost functions by setting relevant coefficients in their nonlinear curves. On the other hand suppliers may utilize these cost curves to produce corresponding bid blocks in order to submit to the market. Similarly, some studies use linear cost curves to build bid blocks, while in some other ones, quadratic cost curves are applied to derive these bid blocks. There are two main types for market clearing mechanism in restructured power markets entitled uniform pricing and pay as bid. In uniform pricing, a unique price is applied to all power producers while in pay as bid system each producer is paid based on its offer. Beside centralized pool market, GenCos may be allowed to sign bilateral contracts with customers that these contracts may affect their bidding strategies.

On the other hand GenCos' bidding may be in form of perfect or imperfect competition markets.

According to some studies suppliers in terms of thermal or hydro units would bid in electricity reserve market besides energy market to achieve the maximum profit. Therefore, this is another interesting aspect in this area. Furthermore, all participants may consider environmental objectives with related monetary objectives as well. It is noticeable that all these studies may accompany with a number of uncertainties. Consequently, stochastic optimization techniques have been employed to solve the problem. According to above mentioned issues this paper represents a complete survey on GenCos' optimal bidding strategy problem.

In this regard, studies are classified in different categories based on market mechanism, trading mechanism, type of competition, transmission security, type of power plant, type of commodity and type of objective function. For each category, the corresponding studies are presented to show the effectiveness of each item. At the end, the impact of uncertainty and risk on GenCos' optimal bidding strategy problem is represented and a number of applicable methods to simulate stochastic nature of the problem are investigated.

## 2. Market Mechanism

An optimal bidding strategy of a generation company (GenCo) that participates in a pay as bid electricity market is developed in [1]. The proposed method is to obtain the Nash equilibrium point for optimal bidding strategy of GenCos considering the risk of the bidding of interested GenCo. The optimal bidding problem is modeled with two optimization sub-problems in which in the first subproblem, each GenCo maximizes its payoff, and in the second sub-problem, a system dispatch will be accomplished. In [2] the problem of energy market price clearing and GenCo strategic bidding is considered with reference to existing day-ahead markets, called system marginal price (SMP) and pay as bid (PAB) auctions. PAB has been proposed as an appropriate alternative to SMP with the aim of increasing competition among GenCos by discouraging collusive behaviors and market power exploitation. Simulations have shown that with the SMP market all GenCos try to improve their profits by implementing such offer strategies as high bid-ups and energy withholding; moreover, the incumbent operator may profit from the exploitation of its market power. This situation is made worse when congestions occur and the GenCos located in importing areas become essential for the load supply. On the other hand according to the PAB market, results show that GenCos' profits are reduced with respect to the SMP case, because of the loss of the infra-marginal revenue. The uniform purchase price paid by consumers is reduced accordingly.

## 3. Trading Mechanism

A risk-constrained method for obtaining bidding curve is presented in [3]. A Day-ahead energy market has been chosen for GenCos competition and the Information Gap Decision Theory (IGDT) is used for modeling day ahead market price uncertainty and its corresponding risk. Bilateral contracts will change the optimization into a two level program. The bilateral contracts of the GenCo are also considered in the proposed framework. A Bi-level optimization problem is utilized in the proposed framework to guarantee a prespecified level of revenue. Ref [4] examines bidding strategies in a bilateral market in which generating companies directly deal with the customer loads. A load accepts electricity from the generator with the lowest bid while this price is equal or lower than the load's willingness to pay. Ref [5] investigates the problem of developing optimal bidding strategies of GenCos, considering bilateral contracts and transmission constraints. The problem is modeled with a two level optimization problem, where in the first level each GenCo maximizes its payoff and in the second level a system dispatch is accomplished through an OPF problem. The impact of local and non local bilateral contracts on GenCos' payoffs is studied. Accordingly it is deduced that in the case when a generator signs a bilateral contract with local consumer, it intends to allocate more energy to bilateral market. Tables 1 and 2 represent pool market and bilateral allocations of GenCo's output for non-local and local bilateral contracts, respectively. Furthermore the higher bilateral prices the more power allocations to these contracts.

Table 1
Optimum Energy Coefficients of Generator for Non-Local Contract [5]

| Bilateral price | 12 | 13 | 14 | 15 | 20 | 24 | 26 |
|---|---|---|---|---|---|---|---|
| Pool market allocation | 88.9 | 86.9 | 84.8 | 82.7 | 72.5 | 64.3 | 60 |
| Bilateral contract allocation | 11.1 | 13.1 | 15.2 | 17.3 | 27.5 | 35.7 | 40 |

Table 2
Optimum Energy Coefficients of Generator for Local Contract [5]

| Bilateral price | 12 | 13 | 14 | 15 | 20 | 24 | 26 |
|---|---|---|---|---|---|---|---|
| Pool market allocation | 51 | 48.6 | 46.2 | 43.8 | 32 | 22.5 | 20 |
| Bilateral contract allocation | 49 | 51.4 | 53.8 | 56.2 | 68 | 77.5 | 80 |

In [6] a linear asymmetric supply function equilibrium (SFE) model with transmission constraints is proposed to develop optimal bidding strategy of suppliers considering forward contracts. Accordingly, forward contracts result in alleviations in GenCos' pricing as well as exerted market power. Nevertheless, transmission constraints lead to some increases in outputs prices.

A mathematical model is presented in [7] to aid a price-taker seller who offers in a bilateral electricity contract auction. Although it was developed to provide support for price-taker sellers, it could also be used by price maker sellers, in case their bids are appropriately bounded at each price level. Ref [8] uses game theory to see whether it is likely that generators bid in their plant at marginal cost or whether it is possible and profitable for them to offer higher prices. It is found that in a market without contracts, bids higher than marginal cost would be under certain circumstances. However, the presence of contracts covering a significant amount of the sold electricity encourages greater use of bids approaching marginal cost. In [9], the supply function model is employed to simulate the bidding strategy of suppliers in the power pool, and various models of supply function equilibrium with future contracts are presented. It is proved that different bidding strategy equilibriums are studied when different intercepts of the bidding curve are chosen.

## 4. Type of Competition

In some studies bidding strategy problem is investigated from price taker units that are not capable to alter market prices [10]. Therefore, the framework of this kind of GenCos could be the same with a perfect competition market. Perfect competition is demanded as a market structure in which there are large numbers of small buyers and sellers, so that all of them act as price-takers. It is known that in a perfect competition market a GenCo would maximize its profits by bidding its true marginal cost function [11].

However, in electricity industry with transmission constraints and limited number of producers, GenCos are facing imperfect competition environments rather than a perfect competition one. Under this condition, each GenCo may increase its own profit through a favorable bidding strategy. In [5] GenCos' optimal bidding strategy is investigated in oligopoly market. Impacts of exercising market power due to transmission constraints as well as irrational biddings of the some generators are studied and the interactions of different bidding strategies on participants' corresponding payoffs are presented. Furthermore, a risk management-based method to obtain optimal bilateral contracts is proposed and the impacts of these contracts on GenCos' optimal biddings and obtained payoffs are investigated. Ref [12] investigates the problem of developing optimal bidding strategies of GenCos in an imperfect competition environment that considers participants' market power as well as transmission constraints. The problem is modeled as a bi-level optimization that at the first level each GenCo maximizes its payoff through strategic bidding, while at the second level, an independent system operator (ISO) dispatches power and solves an optimal power flow (OPF) problem. Table 3 shows unit output characteristics and corresponding payoffs in two cases, perfect and imperfect competition environments. The results clearly indicate the drastic increases in unit payoffs while bidding in imperfect competition market.

TABLE 3
COMPARISON OF GENERATION OUTPUTS, NODAL PRICES AND PAYOFFS IN PERFECT AND IMPERFECT COMPETITIONS [12]

| Units | Perfect competition | | | Imperfect competition | | |
|---|---|---|---|---|---|---|
| | Price | Output | Payoff | Price | Output | Payoff |
| 1 | 5.95 | 98.93 | 195.74 | 12.40 | 92.20 | 788.90 |
| 2 | 7.92 | 17.64 | 54.47 | 12.84 | 29.30 | 174.89 |
| 3 | 10.39 | 7.51 | 35.28 | 13.58 | 9.36 | 63.04 |
| 4 | 9.86 | 39.67 | 131.23 | 13.17 | 28.99 | 217.73 |
| 5 | 10.31 | 14.62 | 53.42 | 13.35 | 16.45 | 102.71 |
| 6 | 10.42 | 14.85 | 55.09 | 13.89 | 16.50 | 103.37 |

In addition, different aspects of exercising market power in terms of transmission congestion and irrational bidding are studied and the corresponding impacts on Nash equilibrium and GenCos' characteristics are proposed. Impact of transmission constraints on exercising market power by generation units are represented in Tables 4 and 5, respectively. Also it not always the case; however as shown, generation units have make use of transmission congestion to exercise market power and increase their corresponding payoffs.

TABLE 4
GAMING RESULTS OF UNCONSTRAINED TRANSMISSION SYSTEM [12]

| Optimal bidding coefficient | Price | Output | Payoff |
|---|---|---|---|
| 2.30 | 15.22 | 115.41 | 1259 |
| 1.07 | 15.61 | 36.70 | 273.20 |
| 1.03 | 16.44 | 11.97 | 95.25 |
| 1.46 | 15.68 | 44.91 | 390.11 |
| 1.07 | 15.98 | 23.87 | 167.41 |
| 1.05 | 16.07 | 24.61 | 170.30 |

TABLE 5
GAMING RESULTS OF CONSTRAINED TRANSMISSION SYSTEM [12]

| Optimal bidding coefficient | Price | Output | Payoff |
|---|---|---|---|
| 3 | 16.32 | 86.01 | 1083.90 |
| 1.13 | 22.99 | 53.03 | 634.62 |
| 1.22 | 31.96 | 20.15 | 370.02 |
| 1.82 | 23.37 | 57.50 | 881.23 |
| 1.63 | 25.21 | 24.93 | 398.33 |
| 3.25 | 34.51 | 15.24 | 422.21 |

Also from another aspect, there are two types of competition games between suppliers entitled cooperative and non-cooperatives games. In the former one, suppliers may cooperate with each other to form a coalition in order to make use of market characteristics and maximize their payoffs while in the latter case each supplier bids individually in the market. In [13] a non-cooperative bidding strategy model is presented with incomplete information in which a supplier can bid a part of its capacity to the market, while self scheduling the remaining part.

A transmission constrained non-cooperative bidding strategy with incomplete information is studied in [11,14] that uses a bi-level optimization associated with DC optimal power flow. In [15] a market with no cooperation is modeled and a Cournot game is solved to simulate oligopoly market equilibrium.

A non-cooperative game with incomplete information is employed in [16] that uses discrete bids, however no other constraint is taken into account. A cooperative game is employed in [17,18] to show the impact of coalitions and collusions among participants.

## 5. CONSIDERING TRANSMISSION CONSTRAINTS

Transmission capacity may lead to congestion, and as a result, the whole electricity market can be actually divided into two or more submarkets. In some studies [2-4] impact of transmission constraints on generators' bidding strategy is neglected. In [19] a stochastic optimization model is used to develop optimal bidding strategies considering network congestion. Here a stochastic optimization model is first formulated under the presumption that the bidding behaviors of rival generation companies could be modeled as normal probability distributions. It is shown that generation companies could utilize transmission congestions to manipulate the market. The proposed method could also be served for roughly analyzing the potential of market power abusing by generation companies under the circumstances of transmission congestions.

One of the signs of transmission security constraints is locational marginal prices (LMPs) that may affect GenCos' optimal bidding strategy. In [20] an OPF-based market price simulator is employed to produce LMPs and generation schedules in each generation node, in which rival competitors' are modeled with probabilities. As the best response to the LMPs and scheduling in its own generation node, the GenCo produces incremental step-cased price output bidding curves with the corresponding probabilities by a market-oriented unit commitment model.

Applying the theory of multiple criteria decision-making (MCDM), the offer with the best compromise among its payoffs as well as market share and its probability is selected as the final bidding results of the GenCo. References [5,12] address the problem of developing optimal bidding strategy for strategic producers in a transmission-constrained day-ahead electricity market. The optimal bidding strategy is formulated as a bi-level optimization problem, where the first level represents the producer profit maximization and the second level represents the ISO market clearing.

The transmission network is incorporated into the ISO problem under two different approaches based on the nodal pricing formulation. The bi-level problem is converted to a mathematical program and is transformed into a mixed-integer linear programming (MILP) model using the Karush–Kuhn–Tucker (KKT) optimality conditions and the strong duality theory. Accordingly, impact of transmission constraints on generators' market power and obtained payoffs may be analyzed.

Another transmission index is reliability. Some papers consider system reliability indices while providing optimal bidding strategy. For instance, a reliability based model is represented in [21] that proposes a supply function model in which system outages in terms of line and unit outages are modeled.

## 6. TYPE OF POWER PLANT

In addition to conventional thermal units other types of units in terms of hydro units can participate in optimal bidding strategy. Ref [22] presents a stochastic midterm risk-constrained hydrothermal scheduling algorithm in a generation company. The objective of a GenCo is to maximize payoffs and minimize financial risks when scheduling its medium-term generation of thermal, hydro, and pump-storage units.

This methodology is used by GenCo for bidding purposes to the ISO. The optimization model is based on stochastic price-based unit commitment. The solution is used to schedule medium-term fuel and water inflow resources for a some months of a year. Test results show that it is necessary to consider the impact of market price, water inflow and generator forced outage uncertainties on medium-term scheduling.

A stochastic mixed-integer linear programming approach to maximize total expected profit of one price-maker hydro producer in a pool-based electricity market is presented in [23]. Head dependence, commitment decisions, discharge ramp rate, startup costs and forbidden zones are all considered in this approach. Uncertainty about the competitors' offers is represented by residual demand curves (RDCs) scenarios. The management of risk is also addressed by conditional value-at-risk (CVaR) to provide the solution sets for which the expected profit may not be augmented without enlarging the variance of profit. Appropriate offering strategies to the pool are also developed, consisting supply functions curves for different risk levels.

An annual stochastic self-scheduling model for a price-maker hydro producer is presented in [24]. In the short term, the producer aims at maximizing profits in the day-ahead market. RDCs model the producer's interaction with his competitors and the load demand. A modification of the RDC is proposed to enable the definition of optimal pumped-hydro bids. Multistage stochastic programming provides hedging against the medium-term uncertainty of inflows, load demand, and competitors' offers. The proposed method models the impact of short-term profit maximization decisions on mid-term scheduling within a compact stochastic mixed integer linear programming (MILP) approach.

Results provide insight on both medium-term reservoir management and short-term market-based operation and indicate the feasibility of solving a large-scale scheduling problem as a unique MILP using a commercial solver. The impact of forward contracts in reducing market power is also analyzed.

## 7. Type of Exchange Commodity

In restructured and de-regulated power systems, generating companies are in charge of supplying for both energy and reserve markets. In this condition, the question is how much and for what price GenCos should generate for each market to maximize their profits. This topic has been investigated in some papers. In [25] 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 that transmission network limitations are not taken into account. Ref [26] develops optimal bidding strategies based on hourly unit commitment in a generation company that participates in energy and ancillary services markets.

The price-based unit commitment problem with uncertain market prices is modeled as a stochastic mixed integer linear program. Test results illustrate that it is necessary to consider market price uncertainty and incorporate stochastic nature of market price in both energy and ancillary markets on the commitment schedule of units. It is also shown that risk constraints would play an important role in deriving biding curves.

The proposed formulation is very practical, which could be applied by GenCos for submitting offers to energy and ancillary service markets. Considering a joint probability distribution function for energy and spinning reserve prices, the bidding problem is modeled as an optimization problem in [27]. The results show that the contribution of GenCos in each market strongly depends on their production costs, GenCo's risk-aversion degree and the mean values of market prices. Moreover, analysis of GenCos' bidding behavior with different production costs is addressed in this environment.

It is shown that the risk of participation in an electricity multimarket, especially for high-cost GenCos, is significantly less than participation in a single market. The results show that the contribution of GenCos in a joint energy and reserve market highly depends on their production costs, their risk aversion degree and mean values of market prices. The contribution of GenCos in these markets poorly depends on standard deviation values of market prices and the correlation between these prices. In [28], at first a joint energy and reserve market is considered, and Nash equilibrium points are determined. Then, the bidding strategies for each GenCo at these points are presented. The bids for the energy and 10 min spinning reserve (TMSR) markets are separated in the second stage and bidding strategies for each GenCo for two separated markets are demonstrated as well.

Comparing the results shows that the separated bidding strategies, while being simplified with the algebraic optimization model give the same results as the combined ones. The problem of building bidding strategies for competitive suppliers in day ahead energy and reserve markets is addressed in [29]. It is assumed that each supplier bids 24 linear energy and spinning reserve supply functions for a day and each market is cleared separately and simultaneously for all 24 delivery hours. A uniform clearing price rule is applied in both markets. The results show the superiority of simultaneous energy and reserve clearing over separated market clearing procedure.

## 8. Type of Objective Function

In a multimarket environment, a GenCo produces electricity subject to a number of factors, including physical and environmental constraints, together with trading strategies in the electricity market (EM), fuel market (FM) and carbon market (CM).

In some papers, the problem of GenCos' optimal bidding strategy in multimarket environment is proposed that allows suppliers to access to the maximum payoffs from arbitrage through these markets. In order to guarantee the generation, with minimum emission, low risk and maximum profit, the linkage between the unit output change and the power price fluctuation is studied in [30], and a mathematical model of optimal unit output in the deal day is established to maximize profit. To assist a GenCo to maximize its profits from EM, FM and CM, [31] proposes a dynamic decision making model with two consecutive stages. Fuzzy differential evolution algorithm is used to solve this decision-making problem.

A rational tradeoff between the profit-making and emission reduction has been demonstrated by the GenCo using the proposed model. From the viewpoint of EM planning, a GenCo would preferably produce energy using as much its wind power as possible, and reduce part of its energy production from high emission units. Furthermore, a GenCo would consider investing in more renewable units with high priority in its production planning.

From CM's viewpoint, a GenCo tends to make a reasonable tradeoff between reducing its emission and purchasing allowances by using the proposed model. The GenCo, which owns wind farm, has advantages to earn more in CM so that it tends to stimulate the power industry to increase the penetration of wind power.

From the standpoint of FM, the fuels cost affects the incremental cost of the thermal units significantly. This model can help GenCos to fully utilize the contracted fuels and decide the trading in the spot market. A GenCo will change its fuel portfolio dynamically with consideration of the price fluctuations in EM, FM and CM. A dynamic decision making model is proposed to deal with the multimarket trading problem for GenCo. During each trading period, the operation of GenCo is divided into production process and trading process. Accordingly, GenCo needs to consider its own production and dispatch its units in the most economical way. Besides, the proposed model also decides when to trade allowance in CM. Comparisons between different scenarios show that the this model can provide good tradeoff between profit making and emission reduction.

## 9. Bidding Strategy in Presence of Uncertainty and Risk

In a competitive electricity market with unknown auction, obtaining optimal bidding strategies for generation companies (GenCos) could be based on some uncertain information. These uncertainties are in terms of price fluctuations, load variations, rivals' strategies and etc. Two main approaches to build stochastic optimal bidding strategies for GenCos are based on mathematical probability theory and heuristic and meta heuristic approaches.

A number of studies have been implemented in order to model existing uncertainties and risks. In this section, corresponding uncertainties and existing methodologies to modeling these uncertainties in bidding strategy problem are investigated. In [32] a framework of random-fuzzy programming is proposed for building optimal bidding strategies with risk management and a hybrid intelligent algorithm by integrating simulation, artificial neural network and genetic algorithm is presented to find optimal bidding strategies.

In [3] a risk-constrained bidding curve construction method is presented. A Day-ahead energy market has been chosen for competition of GenCos and the Information Gap Decision Theory (IGDT) is used for modeling the day ahead market price uncertainty and its corresponding risk. A Bi-level optimization problem is incorporated in the proposed method to guarantee a pre specified level of revenue.

Accordingly, a risk-constrained bidding strategy is derived for a risk-averse GenCo in which a robust performance of IGDT is used in this case. The objective of [33] is to discuss the modeling of auctions of long-term electricity supply contracts. The modeling of different kinds of risks such as price-quantity risk, project, climate change risk, and regulatory risks are discussed. Based on this study appropriate risk management strategy provides investors to devise bids during the auction processes and to support their choices among bidding in different generation options.

In [1] a method is proposed to obtain the Nash equilibrium point for optimal bidding strategy of GenCos considering the GenCo's risk of the bidding.

It is illustrated that in Nash equilibrium point, a GenCo could reduce its payoff, if it unilaterally changes its bidding strategy while the other GenCos' bidding strategies are fixed. In [22] a model is employed to produce GenCos' bids considering rivals' uncertainties. LMPs and schedules in each generation node, with the corresponding probabilities are used to reflect the rival competitors.

An approach of designing the optimal bidding strategies based on incomplete market information is proposed in [34]. This method predicts the expected bidding productions of each rival in the market based on available bidding data. Moreover, the non-linear relationship between generators' bidding productions and the market clearing price (MCP) is also estimated using Support Vector Machine (SVM). The results show that the profits are significantly improved considering rival strategy.

At the time of estimating the uncertain information, generally based on historical trading data, probability methods are used for simulation. However, it depends on statistical characteristics of data thoroughly. When historical trading data is insufficient, probability method is very limited in practice. Therefore, fuzzy set theory method may be applied for bidding strategy and puts forward a method for building optimal bidding strategy.

Ref [35] describes the uncertain information in market with random-fuzzy variables and establishes the random-fuzzy chance constrained mathematical programming model in order to maximize profit under the condition of given confidence level. This method is put forward to build the generation companies optimal bidding strategy under the condition of incomplete information based on the creditability theory.

In [36], the concept of conjectural variation (CV) and its applications in electricity spot markets are introduced. The conjecture of a firm is defined as its belief or expectation of how its rivals will react to the change of its output.

This method can help generation units to improve their strategic bidding and maximize their profits in real electricity spot markets with imperfect information.

With CV based bidding strategy, a firm is able to integrate its rivals into one competitor and estimates its generation and reaction so that an optimal decision can be made accordingly. It is shown that classical game theoretic bidding strategies like Cournot and Stackelberg are special cases of CVBS families. Using CVBS, Nash equilibrium can be easily reached.

Ref [37] considers a thermal unit producer that participates in a day-ahead market in order to maximize its payoff. The producer behaves as a price-taker in the day-ahead electricity market. This study provides the information gap decision theory for determining the optimal bidding strategies for the day-ahead market.

While making bidding strategy, generator characteristics and market price uncertainty need to be considered. Here, a method of building an optimal bidding strategy is presented under market price uncertainty using IGDT. IGDT is a non-probabilistic decision theory that seeks to optimize robustness to failure (risk aversion) or opportunity to windfall (risk taking) under severe uncertainty.

The results show that risk aversion and risk seeking might influence the expected profit and bidding curves of a producer. In [38], an optimal risk based bidding strategy for a generating company (GenCo) by is proposed taking into account self organizing hierarchical particle swarm optimization with time-varying acceleration coefficients (SPSO–TVAC). The Monte Carlo (MC) is also employed to simulate rivals' behaviors in competitive environment.

Test results indicate that the proposed SPSO–TVAC is superior to other combinatorial PSO models. This model is potentially applicable to risk management of profit variation of GenCo and is appropriate for GenCos concerning price risk in spot market. Most of these methods, such as game theory, require a lot of information about the other market players and the market. However, in the real market only a little information, such as the spot price, is available for all participants.

In [39], a modified reinforcement learning based on temperature variation has been proposed and then applied to determine the optimal strategy for a power supplier in the electricity market. A pool market has been considered, and the simulation results are shown to be the same as those of standard game theory.

The main advantage of the proposed method is that it uses the Q-learning algorithm that enables participants to find the optimal strategy using only few information regarding other rivals.

Ref [14] describes a transmission constrained game theory method for analyzing the competition among generating companies with incomplete information. Each GenCo models its opponents' unknown information by means of transforming the incomplete game into a complete game with imperfect information.

The proposed methodology is a bi-level problem that employs supply function equilibrium for modeling a GenCo's bidding strategy. An hourly based optimal bidding strategy for a GenCo that participates in energy and ancillary services markets is represented in [26]. The price-based unit commitment problem with uncertain market prices is modeled as a stochastic mixed integer linear program. The market price uncertainty is modeled using the scenario approach and Monte Carlo simulation is applied to generate scenarios.

Scenario reduction techniques are applied to reduce the size of the stochastic price-based unit commitment problem.

The financial risk associated with market price uncertainty is modeled using expected downside risk. Finally, a stochastic Cournot based optimal bidding strategy is represented in [40] in which uncertainties in rivals' behaviors and market prices are modeled by a price quota curve as illustrated in Fig. 1.

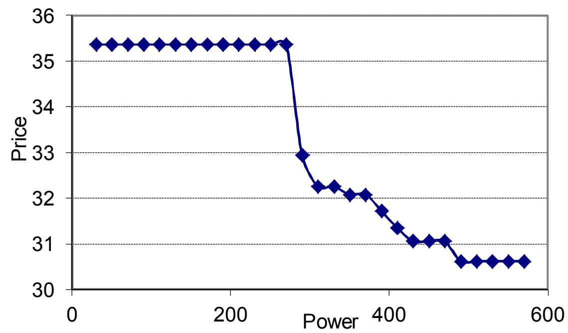


Figure 1: Price quota curve of a generator [40].

This curve represents the impact of each unit contribution on market price variations in an imperfect Cournot based competition market. As it is appear the more contribution results in the lower market prices.

Subsequently, impact of transmission congestion on market clearing prices is discussed as shown in Fig. 2. Accordingly, system congestion results in some increases in market clearing prices, especially in off-peak periods.

However, in peak periods the prices are almost unchanged due to contribution of the most expensive units.

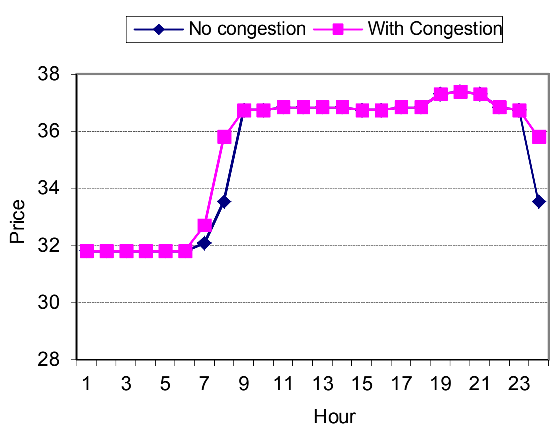


Figure 2: Variation of hourly market clearing prices [40].

In addition, effects of irrational bidding on market characteristics are investigated as illustrated in Fig. 3.

Similarly, one can deduce that exerting market power by irrational bidding of some powerful players leads to increases in hourly market prices.

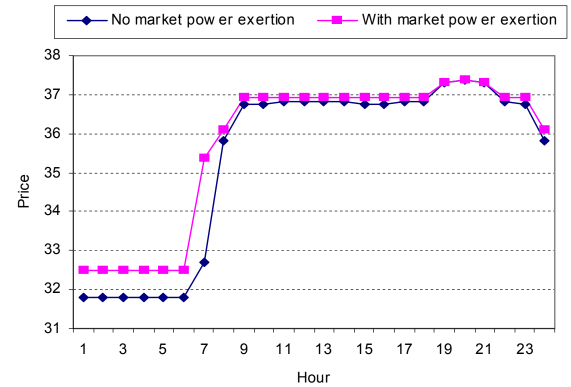


Figure 3: Market prices with and without market exertion [40].

Finally, Table.6 illustrates GenCos' aggregated payoffs in three different scenarios: Cournot equilibrium, after market clearing (without market power), and after implementing security constrained optimal biddings (with market power), respectively. The payoffs are calculated over a period of 24 h.

As shown, GenCos' aggregated payoffs are reduced after clearing the market due to social welfare satisfaction. Here, GenCo1, comprises relatively cheaper units experiences less reduction after clearing the market. As it appears by employing security constrained optimal bidding strategy GenCos have increased their corresponding payoffs. This is the main characteristic of oligopolistic power markets.

TABLE 6
GENCOS' AGGREGATED PAYOFFS IN DIFFERENT SCENARIOS [40]

| Scenario | GenCo1 | GenCo2 | GenCo3 |
|---|---|---|---|
| Cournot output | 123054.9 | 25865.4 | 27369.7 |
| Scheduling without market power | 114873.7 | 23267.7 | 25143.2 |
| Scheduling with market power | 115664.4 | 24659.3 | 26065 |

## 10. CONCLUSION

A comprehensive survey on GenCos' optimal bidding strategy problem is implemented in this paper. In this regard, at first restructured power markets are introduced and the role of GenCos in these competitive environments is represented. Afterward the concept of optimal bidding strategy is introduced. Considering the nature of the problem, optimal bidding strategy may be investigated from different point of views. For this purpose, a novel classification has been made on existing studies implemented in this issue. Accordingly, the studies are classified based on market mechanism, trading mechanism, type of competition, transmission security, type of power plant, type of commodity and type of objective function. For each category, the corresponding studies are presented to show the effectiveness of each item. At the end, the impact of uncertainty and risk on GenCos' optimal bidding strategy problem is represented and a number of applicable methods to simulate stochastic nature of the problem are investigated. The presented paper may be applicable for that group of researches that are interested in GenCos' optimal bidding strategy to give a comprehensive perspective in this issue.

## 11. Acknowledgement

This study was supported by Shahid Rajaee Teacher Training University. Project no: 36850-92/12/27.

## References

[1] Y. Abbasi, N. Bigdeli, and K. Afshar, "Risk-Constrained Optimal Bidding Strategy in Pay-as-Bid Electricity Markets," *IEEE int conference on management and service science*, pp. 1-4, 2011.

[2] F. Careri, C. Genesi, P. Marannino, M. Montagna, S. Rossi, and I. Siviero, "Bidding Strategies in Day-Ahead Energy Markets: System Marginal Price vs. Pay as Bid," IEEE, Energy market, EEM, pp. 1-7, 2010.

[3] M. Kazemi, B. Mohammadi-Ivatloo, and M. Ehsan, "IGDT Based Risk-constrained Strategic Bidding of GenCos Considering Bilateral Contracts," *IEEE, ICEE*, pp. 1-6, 2013.

[4] H. Song, C. Liu, and J. Lawarree, "Nash equilibrium bidding strategy in a bilateral electricity market," IEEE Trans, on POWER SYSTEMS, vol. 17, no. 1, pp. 73-79, 2002.

[5] A. Badri, S. Jadid, M. Rashidinejad, M. P. moghaddam, "Optimal bidding strategies in oligopoly markets considering bilateral contracts and transmission constraints," *Electric Power Systems Research*, vol. 17, pp. 1089-1098, 2007.

[6] H. Niu, R. Baldick, and G. Zhu, "Supply Function Equilibrium Bidding StrategiesWith Fixed Forward Contracts," *IEEE Trans, on POWER SYSTEMS*, vol. 20, no. 4, pp. 1859-1867, 2005.

[7] F. C. Munhoz, P. B. Correia, "Bidding design for price-taker sellers in bilateral electricity contract auctions," Electrical Power and Energy Systems, vol. 30, pp. 491-495, 2008.

[8] N. Lucas, and P. Taylor, "Characterizing generator behavior: bidding strategies in the pool," Butterworth-Heinemann Ltd, 1993.

[9] Z. Yuan, D. Liu, and C. Jiung, "Analysis of equilibrium about bidding strategy of suppliers with future contracts," *Energy Conversion and Management*, vol. 48, pp. 1016-1020, 2007.

[10] A. Conejo, and F. Prieto, "Mathematical programming and electricity markets," *TOP*, 9(1), pp. 1-47, 2001.

[11] V. P. Gountis, A.G. Bakirtzis, "Bidding strategies for electricity producers in a competitive electricity market place," *IEEE Trans. Power Syst.* 19, pp. 356–365, 2004.

[12] A. Badri, and et al, "Impact of generators' behaviors on Nash equilibrium considering transmission constraints," *European transactions on electrical power*, vol. 19, pp. 765-777, 2008.

[13] D. Zhang, Y.Wang, P.B. Luh, "Optimization based bidding strategies in the deregulated market," *IEEE Trans. Power Syst*. 15, pp. 981–986, 2000.

[14] T. Li, M. Shahidehpour, "Strategic bidding of transmission-constrained GenCos with incomplete information," *IEEE Trans. Power Syst*. 20, pp. 437–447, 2005.

[15] F. S. Wen, A.K. David, "Oligopoly electricity market production under incomplete information," *IEEE Power Eng. Rev*. 21, pp. 58–61, 2001.

[16] R. Ferrero, J. Rivera, M. Shahidehpour, "Applications of games with incomplete information for pricing electricity in deregulated power pools," *IEEE Trans. Power Syst.* 13, pp. 184–189, 1998.

[17] R. Ferrero, M. Shahidehpour, V. Ramesh, "Transaction analysis in deregulated power systems," *IEEE Trans. Power Syst*. 12, pp. 1340–1347, 1997.

[18] X. Bai, M. Shahidehpour,V. Ramesh, E.Yu, "Transmission analysis by Nash game method," *IEEE Trans. Power Syst*. 12, pp. 1046–1052, 1997.

[19] L. Ma, F. Wen, Y. Ni, F.F. Wu, "Optimal bidding strategies for generation companies in electricity markets with transmission capacity constraints taken into account," in: Proceedings of the *IEEE/PES Summer Meeting 2*, pp. 2604–2610, 2003.

[20] Y. He, and Y.H. Song, "Integrated bidding strategies by optimal response to probabilistic locational marginal prices," *IEEE Proc.-Gener.* Transmission Distribution, vol. 149, no. 6, 2002.

[21] P. Wang, and L. Goel, "Reliability-based reserve management in a bilateral power market," *Electric Power Systems Research*, vol. 67, pp. 185-189, 2003.

[22] L. Wu, M. Shahidehpour, and Z. Li, "GenCo's Risk-Constrained Hydrothermal Scheduling," *IEEE Trans, on Power Systems*, vol. 23, no. 4, pp. 1847-1858, 2008.

[23] H. M. I. Pousinho, J. Contreras, A. G. Bakirtzis, and J. P. S. Catalão, "Risk-Constrained Scheduling and Offering Strategiesof a Price-Maker Hydro Producer Under Uncertainty," *IEEE Trans, on Power Systems*, pp. , 2013.

[24] C. G. Baslis, and A. G. Bakirtzis, "Mid-Term Stochastic Scheduling of a Price-MakerHydro Producer With Pumped Storage," *IEEE Trans, on Power Systems*, vol. 26, no. 4, pp. 1856-1865, 2011.

[25] F. S. Wen, and A. K. David, "Optimally co-ordinated bidding strategies in energy and ancillary service markets," *IEEE Proc. -Gener*. Transm. Distrib. 149 (2002) 331–338.

[26] T. Li, M. Shahidehpour, and Z. Li, "Risk-Constrained Bidding Strategy With Stochastic Unit Commitment," *IEEE Trans, on Power Systems*, vol. 22, no. 1, pp. 449-458, 2007.

[27] J. Khorasani, and H. RajabiMashhadi, "Bidding analysis in joint energy and spinning reserve markets based on pay-as-bid pricing," *IET Gener*. Transmission Distribution, vol. 6, pp. 79–87, 2012.

[28] S. Soleymania, A.M. Ranjbara, and A.R. Shiranib, "New approach for strategic bidding of GenCos in energyand spinning reserve markets," *Energy Conversion and Management*, vol. 48, pp. 2044–2052, 2007.

[29] F. Wen, and A. K. David, "Coordination of bidding strategies in day-ahead energy and spinning reserve markets," *Electrical Power and Energy Systems*, vol. 24, pp. 251-261, 2002.

[30] P. Chunhua, and S. Huijuan, "Multi-objective Optimal Strategy of Generating and Bidding on Power Selling Side Considering Environmental Protection and Bidding Risk," IEEE Int conference on electric utility deregulation andpower technologies, pp. 263-267, 2008.

[31] X. R. Li, C. WaiYu, ZhaoXu, F. JiLuo, Z. YangDong, and K. P. Wong, "A Multimarket Decision-Making Framework forGENCO Considering Emission Trading Scheme," *IEEE Trans, on Power Systems*, vol. 28, no. 4, pp. 4099-4108, 2013.

[32] X. Ma, "Random-Fuzzy Programming and its Hybrid Intelligent Algorithm to Building Optimal Bidding Strategies for Generation Companies in Electricity Market," International Conference on Computational Intelligence and Security, 2007.

[33] L. A. Barroso, A. Street, S. Granville, and B. Bezerra, "Bidding Strategies in Auctions for Long-Term Electricity Supply Contracts

for New Capacity", *IEEE, Power and energy society meeting*, pp. 20-24, 2008.

[34] X. Yin, J. Zhao, T. Kumar Saha, and Zh. Yang Dong, "Developing GenCo's Strategic Bidding in an Electricity Market with Incomplete Information," IEEE, Power and energy society meeting, pp. 1-7, 2007.

[35] J. Liu, Q. Zhu, X. Ma, and Q. Ding, "Random-Fuzzy Programming Based Bidding Strategies for Generation Companies in Electricity Market Environment," International Conference on Sustainable Power Generation and Supply, 2009.

[36] Y. Song, Y. Ni, F. Wen, Zhijian Hou, and F. F. Wu, "Conjectural variation based bidding strategy in spot markets: fundamentals and comparison with classical game theoretical bidding strategies," *Electric Power Systems Research*, vol. 67, pp. 45-51, 2003.

[37] S. Nojavan, K. Zare, and M. R. Feyzi, "Optimal bidding strategy of generation station in power market usinginformation gap decision theory (IGDT)," *Electric Power Systems Research*, vol. 96, pp. 56– 63, 2013.

[38] Ch. Boonchuay, and W. Ongsakul, "Optimal risky bidding strategy for a generating company by self-organising hierarchical particle swarm optimization," *Energy Conversion and Management*, vol 52, pp. 1047–1053, 2011.

[39] M. B. Naghibi-Sistani, M. R. Akbarzadeh-Tootoonchi, M.H. Javidi-DashteBayaz, and H. Rajabi-Mashhadi, "Application of Q-learning with temperature variation for bidding strategies in market based power systems," *Energy Conversion and Management*, vol. 47, pp. 1529–1538, 2006.

[40] A. Badri, and M. Rashidinejad, "Security constrained optimal bidding strategy of GenCos in day ahead oligopolistic power markets: A Cournot based model," *Electrical Engineering, Springer*, vol. 95, pp. 63-72, 2013.

## BIOGRAPHIES

**Ali Badri** received the B.Sc. degree in electrical engineering from Isfahan University of Technology in 1995 and the M.Sc.and PhD degrees from Iran University of Science and Technology, Tehran, in 2000, 2008, respectively. He is currently an assistant professor in the faculty of Electrical Engineering Shahid Rajaee Teacher Training University. His research interests are restructured power systems, power system optimization, power system operation and planning and renewable energy.