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Nash equilibrium strategies of generating companies (Gencos) in the simultaneous operation of active and reactive power market, with considering voltage stability margin

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ABSTRACT

As Gencos are responsible for providing active and reactive power generation, they should devise good bidding strategies for energy and reactive power market. The paper describes a method for analyzing the competition among transmission-constrained Gencos with incomplete information. The proposed methodology employs the Supply Function Equilibrium (SFE) for modeling a Genco's bidding strategy in energy market and uses Expected Payment Function (EPF) to construct a bidding framework in the reactive power market. The problem of finding the optimum strategy of Gencos is modeled as a bi-level optimization problem, where the upper sub-problem represents individual Genco's payoff and the lower sub-problem solves the ISO's market clearing problem. The ISO's market clearing model is modified with applying generator Active Participation Factors to improve the voltage stability margin. The IEEE 39 bus test system is used to verify the effectiveness of the proposed method.

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1. Introduction

Since 1980, the electricity market has been gradually evolved from a monopoly market into a liberalized one for encouraging competition and improving efficiency. These new conditions bring the opportunity for Gencos to make more profits while embracing more risks of not being dispatched. Therefore, it has become a core interest for Gencos to develop optimal bidding strategies in different markets to maximize the profit and minimize the risk while participating in such competitive markets. These markets are energy and, ancillary service markets, such as reserve and reactive power markets.

In this environment, Gencos are very interested in selling their outputs at higher prices, but due to the competition, they may be eliminated from the market in some hours because of their bid being too high in price or being on rational in amount. Therefore the Gencos should devise good bidding strategies in these markets, according to their opponents' bidding behaviors, the model of demand, the type of ancillary service market, and power system scheduling process. In the power system, ISO uses a security-constrained economic dispatch to clear the market after receiving bids [1–3].

Based on the following reasons, Gencos should take the best decision about their bids at the reactive power market:

1. The locations of reactive power compensators are very important in the reactive power market. A low cost reactive producer may not essentially be favorable if it is far from the consumer. Vice versa, a high cost local reactive compensator at a heavily loaded demand center of network could be inevitably an alternative required to produce reactive power to maintain the integrity of power system [4].
2. Based on generator's capability curve [5], the generating unit may reduce its active power output to meet the field heating limits when higher reactive power is offered.

Based on the above reasons, devising a good bidding strategy for Gencos in the active and reactive power markets is one of the most difficult problems with a large number of unknown variables.

There are two methods for developing bidding strategies in electricity markets: game based and non-game based methods [6]. The game based methods, which will be used in this article, utilize game theory to simulate the bidding behavior of Gencos and develop Nash equilibrium bidding strategies for them in energy and reactive power markets.

In [7], a comprehensive literature analysis has been carried out on the state-of-the-art research of bidding strategy modeling methods. In [8], based on the coordinated interaction between

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Nomenclature

I	index of block
J	index of Generator
ρ	bidding price
K	bidding strategy of generator
MC	marginal cost
$C()$	generation cost function
a, b, c	generation cost coefficients
P	the offered or awarded quantity
Q	reactive power
ω, ω'	weighting Factor for active and reactive power market
N	total number of Generators
$P^{\min}, P^{\max}$	minimum and maximum generation limit of generators
P^G	active power bus generation
P^D	active power bus load
V	bus voltage
δ	bus angle
$V^{\min}, V^{\max}$	minimum and maximum voltage limit
S_{bl}	apparent power of branch l
R	pay off function
K_{FC}	angular coefficient of field current limit line
LMP	locational marginal price
$\Delta P, \Delta Q$	vector of bus active and reactive power injection variations
$\Delta\theta, \Delta V$	vector of bus angle, and bus voltage magnitude variations

Genco's output and electricity market prices, the benefit/risk/emission comprehensive generation optimization model with objective of profit maximization and bidding risk and emissions minimization is established. A stochastic framework for clearing of day-ahead reactive power market was presented on [9]. In this paper the uncertainty of generating units in the form of system contingencies are considered in the reactive power market-clearing problem by the stochastic model in two steps. In the first step, the Monte-Carlo Simulation is first used to generate random scenarios. Then, in the second step, the stochastic market-clearing procedure is implemented as a series of deterministic optimization problems (scenarios) including non-contingent scenario and different post-contingency states.

The model presented in this paper employs Supply Function Equilibrium (SFE) model for Gencos to bid at energy and reactive power markets, and game theory concept is used to investigate the best bidding behavior of Gencos. The power system is represented using non linear AC power flow analysis in order to include the modeling of reactive power in the system and enhance the accuracy of the electricity market. The competition is modeled as a bi-level optimization problem, while upper sub problem representing the individual Genco and the lower sub problem representing the independent system operator (ISO). To improve voltage stability margin, Active Participation Factors of generators are used in ISO's market clearing problem for selecting generators on reactive power market.

The paper is organized as follows: The problem formulation, and the proposed solution method are presented in Sections 2, and 3. Section 4 gives the illustrative example with 10 units. Section 5 provides the conclusion.

2. Problem formulation

2.1. Preparing bid for energy and reactive market

In a power market, Gencos may prepare their strategic bids according to the four known models in imperfect competition, i.e. some firms (the strategic players) are able to influence the market price through their actions. These models include Bertrand, Cournot, Stackelberg and Supply Function Equilibrium (SFE) where Stackelberg model is similar to the Cournot model [1]. In the Bertrand model, Gencos compete each other using prices as strategy choices and in the perfect competition, they bid at their marginal cost. In the classic model of Cournot, Gencos compete against each other using quantities as strategy choices. In this model Genco's products are assumed to be homogenous, demand is price-responsive, and Market Clearing Price (MCP) is the intersection of aggregated supply and market demand curves. Stackelberg model is similar to the cournot model. However, the competitors do not offer their output quantities simultaneously. The so-called "leader" will make the first movement, which is followed by that of followers who take into account the leader's action [6]. In the SFE model, Gencos compete with each other through the simultaneous choice of supply functions. Klemperer and Meyer developed SFE in order to model competition in the presence of demand uncertainty. The SFE model was used by Green and Newbery for analyzing the competitive strategic bidding in electricity markets [6,12]. Among these models, it is only the SFE model in which a Genco links its bidding price with the bidding quantity of its product, and only this model is the closest to the actual behavior of players in the actual power market.

Let us suppose that the Gencos are requested to submit a piece wise quantity-price curve like the one shown in Fig. 1 for each generator to the ISO for the energy market. Accordingly, for the jth generator, the Gencos would devise their own bid segments according to the linear supply function [13]:

$$\rho_{ji} = k_j \cdot MC_{ji} = k_j \cdot (2a_jP_{ji} + b_j)$$

where

$$C_{ji} = C(P_{ji}) = a_jP_{ji}^2 + b_jP_{ji} + c_j$$

The bid pairs submitted to the markets are:

$$(P_{j1} - P_{\min}, \rho_{j1}), (P_{j2} - P_{j1}, \rho_{j2}), (P_{j3} - P_{j2}, \rho_{j3})$$

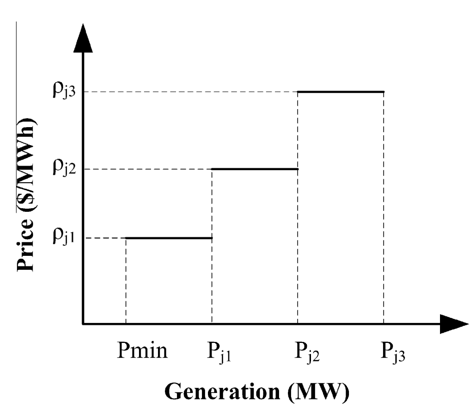

Fig. 1. Genco's bid curve for generator j in the energy market.

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