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Strategic bidding for wind power producers in electricity markets

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A B S T R A C T

In evolving electricity markets, wind power producers (WPPs) would increase their profit through strategic bidding. However, generated power by WPPs is highly random, which may result into heavy imbalance charges. In markets dominated by wind generators, they would optimize their offered bids, considering rival behavior. In oligopolistic day-ahead electricity markets, this strategic behavior can be represented as a Stochastic Cournot model. Wind uncertainty is represented by scenarios generated using Auto Regressive Moving Average (ARMA) model. With a consideration of wind power uncertainty and imbalance charges, strategic WPPs can maximize their expected payoff or profit through the proposed Nash equilibrium based bidding strategy. Nash equilibrium is obtained using payoff matrix approach. Proposed approach is evaluated on two realistic case studies considering different technical constraints. Obtained results shows that proposed bidding strategy mechanism offers quantum increase in profit for WPPs, when their behavior is modeled in a game theoretic framework. Flexibility of approach offers opportunities for its extension to associated challenges.

1. Introduction

Power sector is being restructured worldwide, with an aim to improve system efficiency and offer economic solutions. At the same time, uncertainties in fossil fuel prices and environmental concerns are enhancing the quantum of wind power generation [1]. Over the last few decades, governments over the world are trying to increase the contribution of green energy in electricity supply, by providing subsides and support schemes [2].

Evolving deregulated electricity markets are primarily designed for conventional or fossil fuel generators. These markets operate on a day-ahead timeline, where participants commit their generated power several hours before actual power delivery. Eventual power delivered by wind generators differs from their initial commitment due to intermittent nature of wind. Participants deviating from their committed schedule face penalties. Small capacities and random generation restrict the WPPs to act as strategic players. They participate in the market as 'price takers', and are not able to affect the market prices. Due to high capital cost and imbalance penalties, they cannot operate profitably in pool-based electricity markets. Therefore, they are forced to sell their power through bilateral contracts.

In pool-based electricity markets, conventional generators can increase their profit by optimal bid formulation using various bidding strategy models. Bidding strategy models are broadly classified into two categories, *i.e.* game-theoretic and non-game theoretic models [3–19]. These models become stochastic when uncertainties like demand, unit availability, fuel price, and wind are incorporated in it [6–10]. Stochastic models developed for optimal bid formulation of WPPs help to minimize their imbalance cost. With a consideration of forecasting window length and market closure delay, Markov Probability based stochastic model can determine the optimal contracted energy level [11,12]. Multistage stochastic programming approaches suggest various trading floors to derive the best offering strategy for a wind generator [13]. Uncertainties such as wind availability, day-ahead market price, adjustment market price and balancing market price, along with profit risk measures, have been considered. However, wind generators are still assumed to be price-takers. In addition, focus is on increasing the wind generator's profit by bid selection, with minimum imbalance cost. Opportunity cost based analytical approach can optimize bids of price-taker WPP in forward electricity market [14]. Strategic gaming by WPPs for bid selection in pool based electricity markets has generally been neglected.

With the present thrust and growth, in the near future, WPPs would increasingly supply power to an extent of 20% or more of market demand [15]. They would participate in pool based electricity markets strategically, without any regulatory support and

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Nomenclature

Sets or indices

Ω^g set of indices of conventional GENCOs
Ω^d set of indices of demands
Ω^w set of indices of WPPs
$\Omega^{n/r}$ set of indices of buses
Ω^{n-r} set of indices of transmission lines
Ω^{ω} set of indices of scenarios
Ψ_n^g mapping of conventional GENCOs located at bus n
Ψ_n^d mapping of demand located at bus n
Ψ_n^w mapping of WPPs located at bus n
Υ_l^d set of indices of lth blocks of dth demand

Constants or parameters

B_{n-r} susceptance of line $n-r$ (per unit)
$f_{n-r}^{\max}$ power transfer capacity of transmission line $n-r$ (MW)
$P_{d,l}^{\max}$ upper limit of lth block of dth demand (MW)
$P_g^{\max}$ installed capacity of gth conventional GENCO (MW)
$P_i^{\max}$ installed capacity of ith WPP (MW)
$\lambda_{d,l}$ marginal utility cost of lth block of dth demand (MW)
λ_g marginal cost of gth conventional GENCO (MW)
$\text{prob}_{\omega,t}$ weight (or occurrence probability) of scenario ω at time t
DF_t demand factor at time t (per unit)

Variables

$f_{n-r,t}$ power flow through transmission line $n-r$ at time t (MW)
$P_{d,l,t}$ power scheduled to be consumed by lth block of dth demand at time t (MW)
$P_{g,t}$ power scheduled to be produced by gth conventional GENCO at time t (MW)
$\Delta_{i,\omega,t}$ power bought from/sold to balancing market by ith WPP at time t (MW)
$IC_{i,\omega,t}$ imbalance charges of ith WPP at time t ($)
$Pof_{i,t}$ power offered to day-ahead market by ith WPP at time t (MW)
$P_{i,\omega,t}$ power produced by ith WPP in scenario ω at time t (MW)
$\delta_{n,t}$ voltage angle at bus n at time t (rad.)
$\lambda_{n,t}$ locational marginal price at bus n at time t ($/MW h)
$\lambda_{n,t}^+$ positive imbalance price at bus n at time t ($/MW h)
$\lambda_{n,t}^-$ negative imbalance price at bus n at time t ($/MW h)
$\lambda_{n,t}^{UP}$ upward balancing market price at bus n at time t ($/MW h)
$\lambda_{n,t}^{DN}$ downward balancing market price at bus n at time t ($/MW h)

benefits. They would tend to increase their profit by gaming in the market [16]. Strategic WPP can optimize their offering strategy either in day-ahead and balancing markets using stochastic mathematical program with equilibrium constraints approach [17,18]. The duopoly competition between strategic power producers, consisting of wind generators as a part of their portfolio, has been modeled using equilibrium problem with equilibrium constraints approach [19].

This paper focuses on formulation of optimal offering strategy for multiple independent strategic WPPs, in a market dominated by intermittent wind generation. Strategic behavior of WPPs in network constrained oligopolistic day-ahead electricity markets, considering wind uncertainty, is modeled using Stochastic Cournot model. In this model, WPPs aim to maximize profit by offering optimal bids, considering rival behavior and complete information. Imbalance charges consider strategic WPPs' profit calculation using location based dual imbalance price mechanism. Solution of the proposed model is Nash equilibrium, obtained by payoff matrix approach. Proposed game-theoretic bidding strategy approach is illustrated through two practical case studies with three independent strategic WPPs.

Rest of the paper is organized as follows. In Section 2, the market structure, uncertainty characterization, and Stochastic Cournot model are described. Section 3 provides mathematical modeling of the problem and the simulation procedure. Section 4 includes numerical and graphical results of testing the proposed model through a comprehensive analysis on three WPPs located at different locations. In Section 5, relevant conclusions are drawn.

2. Problem description

2.1. Market structure

WPPs participate in network constrained pool based day-ahead electricity market, cleared several hours before actual power delivery. Real-time balance between supply and demand is maintained by the balancing market, few minutes before power delivery. Independent System Operator (ISO) manages operation of both day-ahead and balancing market. WPPs are considered as strategic power producers in only day-ahead electricity market, while in balancing market they participate non-strategically. WPPs get imbalance charges for their real-time generation deviations. This consideration realistically reflects electricity markets as electricity is traded largely on day-ahead timeline. Due to low liquidity of adjustment or intra-day market, participation of strategic WPPs in this market is neglected.

Imbalance charges resulting from balancing market are charged to generators causing that system imbalance. In this work, location based dual imbalance price mechanism is considered for imbalance charging, as widely used in European markets such as UK's New Electricity Trading Arrangements (NETA), Nord Pool, and Iberian Peninsula [2,11–14].

In a location based dual imbalance price mechanism, generators are charged for their positive and negative deviation, reflecting system imbalance and their locations. This location based dual imbalance price mechanism can be treated as a traditional dual imbalance price mechanism for uncongested systems. For positive system imbalance, other Generation companies (GENCOs) would like to purchase excess energy at a downward price $\lambda_{n,t}^{DN}$, lower than LMP $\lambda_{n,t}$ of their location. In this case, generators producing excess power than scheduled get a downward payment for their overproduction. On the other hand, generators producing lower than their scheduled production are penalized as per the LMP. Positive imbalance price (PIP) and negative imbalance prices (NIP) at a particular location during system surplus are mathematically expressed as

$$\lambda_{n,t}^+ = \min(\lambda_{n,t}, \lambda_{n,t}^{DN}) \tag{1}$$

$$\lambda_{n,t}^- = \lambda_{n,t} \tag{2}$$

With negative system imbalance, generators are willing to provide the energy needed to cover negative imbalance at LMP. In this case, generators producing excess power than scheduled, get