Impacts of Strategic Bidding of Wind Power Producers on Electricity Markets

Mohsen Banaei, Majid Oloomi Buygi, *Member, IEEE*, and Hamidreza Zareipour, *Senior Member, IEEE*

***Abstract*—In this paper, the impacts of strategic bidding of a wind power producer on electricity markets are studied. To this end, the strategic bidding of a wind power producer is investigated under the following three schemes: 1) the wind power producer sets its generation power while other producers set their supply functions, 2) the wind power producer sets its supply function and so do other producers, and 3) the wind power producer teams up with a non-wind generating firm and the aggregated firm sets its supply function and so do other producers. Supply function equilibrium models are used to determine the strategic behavior of generating firms at market equilibrium. Illustrative numerical results are provided.**

***Index Terms*—Wind generation, strategic bidding, market equilibrium.**

ABBREVIATIONS

Firms

NGF	Non-wind Generating Firm
WPP	Wind Power Producer

Schemes

GP scheme	Generation Power scheme
PT scheme	Price-Taker scheme
SF scheme	Supply Function scheme
WN scheme	Wind and Non-wind coalition scheme

Others

ISO	Independent System Operator
KKT	Karush-Kuhn-Tucker
MCP	Market Clearing Price
PDF	Probability Density Function
SFE	Supply Function Equilibrium

I. INTRODUCTION

WPPs are moving towards strategic participation in competitive electricity markets. Several ISOs across the world have mechanisms to allow WPPs to bid in competitive electricity markets, such as NYISO, MISO, PJM, and ERCOT [1]. Most recently, the Alberta electric system operator initiated a pilot project to explore the opportunities and challenges of having wind generators participating in the market [2]. Following the pilot project, WPPs in Alberta, Canada, are given the option to submit offers to the market since April 1, 2015.

The unpredictable nature of wind power may cause imbalances between scheduled generation and consumption. Hence, electricity markets with large-scale wind power integration require more reserve to cover balancing issues. Consumers are usually responsible to pay for the cost of balancing power. However, in some power systems, WPPs are charged for balancing costs to encourage them to further invest in wind energy forecasting [3]. Thus, there is a cost for the uncertainty associated with wind power, which may impact wind generators' strategic behavior.

Several studies have been reported in the literature on the strategic behavior of WPPs. The literature mainly, focuses on determining the optimal values of price or quantity of WPPs' bids in the short-term. In [4], stochastic programming is used to generate optimal bidding strategies for wind and conventional power producers in both energy and reserve markets. Reference [5] proposes a probabilistic methodology for estimating the economic impact of wind prediction errors on the costs of wind energy. In [6], it is shown that WPPs can increase their revenue by optimally bidding in both energy and reserve markets; accordingly, part of wind power variations is diverted into the system reserve, reducing the need for additional reserve required to balance short-term variations of wind power.

References [1] and [7]–[13] compute the optimal strategy of a strategic WPP. In [7], the WPP is considered as a price-taker in day-ahead market and as a price-maker in balancing market. In [8] interval optimization is used to find optimal bidding strategy of a joint WPP and hydro station operation in day-ahead electricity markets. Impacts of forming coalitions between renewable power producers on uncertainty reduction, market power, and strategic bidding of renewable power producers in day-ahead electricity markets are studied in [9]. Reference [10] proposes a mixed-integer linear program to find the optimal bid of a WPP as a price-maker in both day-ahead and real-time markets. In [11] optimal bidding strategy of a WPP in intraday markets is investigated through a stochastic optimization problem considering the uncertainty of balancing prices and intraday market price. In [12], the WPP is considered as a price-maker in day-ahead market and as a deviator in balancing market. In [13], the WPP is strategic in both day-ahead and balancing markets. In [1], the WPP acts strategically in both day-ahead and real-time markets. Proposed models in [1] and [13] consider uncertainties in wind-power productions,

Manuscript received May 26, 2015; revised September 19, 2015 and December 12, 2015; accepted January 20, 2016. Date of publication February 19, 2016; date of current version October 18, 2016. Paper no. TPWRS-00746-2015.

M. Banaei is with Ferdowsi University of Mashhad, Mashhad, Iran.

M. Oloomi Buygi and H. Zareipour are with the Department of Electrical and Computer Engineering, University of Calgary, Calgary, AB T2N 1N4, Canada (e-mail: moloomib@ucalgary.ca).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2016.2524993

demand, and rivals' offers by identifying a possible set of scenarios.

The contributions of this paper are as follows. In this paper a mathematical equilibrium model for electricity markets with a strategic WPP is presented. A new scheme for strategic bidding of WPPs in electricity markets is proposed. In this scheme, the WPP teams up with a NGF and the aggregated firm participates in electricity markets as a single strategic firm. To improve the accuracy of wind generation uncertainty modeling, an approach for incorporating historical wind power forecasts data in uncertainty modeling is proposed. The impacts of strategic behavior of a WPP under the proposed scheme and under the schemes, which are introduced in [14], [15], are compared. Finally, the influences of balancing prices, teaming up with different NGFs, operation cost, load level, price elasticity of load, load uncertainty, and transmission congestion are assessed.

References [1] and [7]–[13] modeled the bidding strategy of a WPP using mathematical programming with equilibrium constraints (MPEC). However, the present paper presents an equilibrium model for electricity markets with a strategic WPP. This model is an equilibrium problem with equilibrium constraints (EPEC). In other words, [1] and [7]–[13] solve the problem from the viewpoint of a WPP, whereas this paper solves the problem from the viewpoint of the market regulator. The significance of this model is that it enables market regulators to study the impacts of strategic bidding of WPPs on electricity markets and promoting desirable frameworks for strategic participation of WPPs in electricity markets.

The remainder of this paper is organized as follows: In Section II, the main assumptions and the required background are reviewed. SFE under the proposed schemes for strategic bidding of WPPs is modeled in Section III. Modeling uncertainty is discussed in Section IV. To determine the impacts of strategic bidding of WPPs, case studies are presented and analyzed in Section V. Finally, conclusions are presented in Section VI.

II. Assumptions and Background

A. Assumptions and Problem Definition

In this paper, a day-ahead pool electricity market with strategic NGFs is considered. Transmission constraints are ignored to avoid the impacts of transmission constraints on strategic behavior of WPPs and consequently on generality of the final results. However, we have discussed how transmission constraints could be integrated in the model. It is assumed that each generating firm offers a linear supply function to ISO. The ISO determines power generation dispatch quantities and market price by maximizing the social welfare considering generation constraints. It is assumed that each generating firm is responsible for unit commitment of its generators. Hence, unit commitment constraints such as minimum up/down time limits, ramp rate limits, and maximum/minimum energy limits are ignored in the ISO optimization. Accordingly, the ISO can maximize social welfare for each hour independently. Here, we focus on one hour of the next day (e.g., peak load). We assume that applicable market rules allow WPPs to participate in energy market strategically and allow coalition between a WPP and a NGF. Note that this may require changes to existing market structures, and may not necessarily be the case in today's market rules.

B. Overview and Methodology

Suppose that a large-scale WPP is added to the power grid. In order to study the impacts of strategic bidding of the WPP, it is important to know the bidding strategies of NGFs when the WPP behaves strategically. To model the strategic bidding of the WPP and NGFs, it is assumed that the market has approached its Nash equilibrium. Since supply function model is less sensitive to its parameters than Cournot model and since it represents the reality of electricity markets better than Cournot and Bertrand models [16], linear SFE model is used to determine the strategic bidding of generating firms at market Nash equilibrium. Linear SFE gives an acceptable approximation of market behavior [17], and thus, linear SFE model is used here. In real-life markets, stepwise supply functions are used [12]. Incorporating such functions are not within the scope of the present work.

The study horizon is a medium-term horizon, i.e., one or a few months in the future. The impacts of strategic bidding of the WPP are assessed at the Nash equilibrium of the market under the proposed schemes. To improve the accuracy of wind generation uncertainty modeling, historical wind power forecasts data are used to identify the possible future scenarios of wind power. Wind power uncertainty is modeled by considering possible future scenarios of wind power generation. In the presented SFE model, the WPP determines its bid by maximizing its expected profit over all wind power scenarios. Since the power imbalance resulting from wind power uncertainty is covered by balancing units, NGFs do not observe wind uncertainty. Hence, NGFs determine their bids by maximizing their profit in a deterministic environment. Deterministic SFE model is reviewed in the next subsection.

C. Deterministic SFE Model

Consider a uniform electricity market, i.e., one price applies to all transactions across the market and thus, price is not locational-based. Suppose the marginal cost of NGF f is $MC_f = a_f + b_f Q_{sf}$ and the marginal utility of consumer j is $MU_j = c_j - d_j Q_{Dj}$, where Q_{sf} and Q_{Dj} are generation power of firm f and consumption power of consumer j respectively. Each firm f submits a linear supply function, $\rho_{bid}(Q_{sf}) = \alpha_f + b_f Q_{sf}$, to the ISO. It is assumed that the slope of supply function of firm f, b_f, is constant and equal to the slope of its marginal cost. The objective of the ISO in day-ahead scheduling is to determine MCP and firms' generation powers by maximizing the social welfare. The ISO's social welfare optimization problem is shown as below:

$$Max\ J_{ISO} = \sum_{i\in D}\left(c_i Q_{Di} - \frac{d_i}{2}Q_{Di}^2\right) - \sum_{f\in F}\left(\alpha_f Q_{sf} + \frac{b_f}{2}Q_{sf}^2\right) \quad (1)$$

$$s.t: \sum_{f\in F} Q_{sf} - \sum_{i\in D} Q_{Di} = 0 \quad (2)$$

$$0 \le Q_{sf} \le Q_{sf}^{max} \qquad \forall f \in F \quad (3)$$

where J_{ISO} is social welfare, Q_{sf}^{max} is the capacity limit of firm f, F is the set of generating firms, and D is the set of consumers. On the other side, the goal of firm f is to determine the parameter α_f to maximize its profit. The optimization problem of firm f can be modeled as follows:

$$Max \qquad \pi_f = \lambda Q_{sf} - a_f Q_{sf} - \frac{1}{2} b_f Q_{sf}^2 \quad (4)$$

$$s.t: \ optimization\ problem\ (1)-(3) \quad (5)$$

where π_f is the profit of firm f and λ is the MCP. SFE problem can be formulated by the set of coupled bi-level optimizations (4)–(5) for every $f \in F$. An approach to solve these coupled bi-level optimizations is to replace the inner-level optimization problem, i.e., (5) or (1)–(3), with its KKT optimality conditions, and then solving the KKT optimality conditions of the outer-level optimization problems together, i.e., (4) subject to KKT conditions of (5) for all firms. By replacing the inner-level optimization problem with its KKT conditions and simplifying it, the profit of firm f can be written as a quadratic function of α with negative second derivative, as follows [18]:

$$\pi_f = (\boldsymbol{\alpha}+\boldsymbol{\mu})^T \boldsymbol{Q_f}(\boldsymbol{\alpha}+\boldsymbol{\mu}) + (\boldsymbol{\alpha}+\boldsymbol{\mu})^T \boldsymbol{R_f} + ((\boldsymbol{\alpha}+\boldsymbol{\mu})^T \boldsymbol{R'_f} + s'_f)Q_{D0} + s''_f Q_{D0}^2 \quad (6)$$

where n_g is the number of all NGFs, $\boldsymbol{\alpha}$ is a $n_g \times 1$ vector which consists of the bids of all NGFs, $\boldsymbol{\mu} = \boldsymbol{\mu^{max}} - \boldsymbol{\mu^{min}}$, and $\boldsymbol{\mu^{max}}$ and $\boldsymbol{\mu^{min}}$ are $n_g \times 1$ vectors which consist of the dual variables of upper and lower generation limits respectively. The elements of $n_g \times n_g$ matrix $\boldsymbol{Q_f}$, $n_g \times 1$ vectors $\boldsymbol{R_f}$ and $\boldsymbol{R'_f}$, and scalars S'_f, S''_f and Q_{D0} depend on the parameters of marginal cost of the NGF f i.e., a_f and b_f, and the slope of the bid functions of the other NGFs i.e., $b_i\ \forall i \in F$, and are defined in Appendix A. In fact, Q_{D0} is the sum of intercepts of demand functions. SFE model consists of the KKT conditions of the outer-level optimizations of all firms. The SFE model can be simplified as follows [18]:

$$\boldsymbol{H}(\boldsymbol{\alpha}+\boldsymbol{\mu}) + \boldsymbol{R} + \boldsymbol{R'}Q_{D0} - \boldsymbol{U\mu} = 0 \quad (7)$$

$$\boldsymbol{V}Q_{D0} + \boldsymbol{U}(\boldsymbol{\alpha}+\boldsymbol{\mu}) \le \boldsymbol{Q_s^{max}} \quad \perp \quad \boldsymbol{\mu^{max}} \quad (8)$$

$$\boldsymbol{V}Q_{D0} + \boldsymbol{U}(\boldsymbol{\alpha}+\boldsymbol{\mu}) \ge \boldsymbol{0} \quad \perp \quad \boldsymbol{\mu^{min}} \quad (9)$$

where the elements of $n_g \times n_g$ matrix $\boldsymbol{H}$, $n_g \times 1$ vectors $\boldsymbol{R}$, $\boldsymbol{R'}$, $\boldsymbol{V}$, and $\boldsymbol{U}$ depend on the coefficients of marginal cost functions of firms and marginal utility of consumers and are defined in Appendix A. By solving (7)–(9), the SFE, i.e., $\alpha_f^*\ \forall f \in F$, is computed. In [18], it is shown that the optimal strategy of firm f at SFE of the proposed electricity market model does not depend on the bids of bound firms at the SFE. A bound firm at SFE is a firm that one of its generation limits is active at the SFE. Hence, bound firms at the SFE must be identified and eliminated from SFE model, i.e., (7)–(9). An algorithm for computing probabilistic SFE is presented in [18]. The algorithm can be easily used for computing deterministic SFE assuming there is only one scenario for uncertainty. At each stage of this algorithm, (7)–(9) are solved. The largest dual variable associated with generation limits is identified and the related firm is omitted. Omitting a firm means fixing its output power at its active limit and subtracting its active power generation limit from the load. This process continues until all bound firms are identified, omitted, and SFE is computed.

III. Alternative Schemes for Strategic Bidding of the WPP

In this section, the market's SFE is modeled under the proposed schemes for strategic bidding of the WPP. Wind uncertainty is modeled by considering possible scenarios in the study horizon. Suppose $Q_{w_1}, Q_{w_2}, \ldots, Q_{w_k}, \ldots, Q_{w_{n_k}}$ are the wind power of different scenarios associated with probabilities of $p_1, p_2, \ldots, p_k, \ldots, p_{n_k}$. In the following subsections, first, the WPP is modeled as a price-taker firm and then it is modeled as a strategic firm under the proposed schemes.

In real time, wind power generation is most likely different from the value considered in day-ahead scheduling. It is assumed that the ISO covers the imbalance using a balancing utility. The balancing utility has some flexible loads and generating units. These units are called balancing units and are able to increase or decrease their generation. It is assumed that consumers are charged for balancing cost in the price-taker scheme, whereas the WPP is charged for balancing cost in the proposed strategic schemes. To explain how the WPP pays the balancing cost, suppose Q_{sw} is scheduled generation power of the WPP for the understudy hour in the first or second proposed strategic scheme. Q_{sw} is determined by the ISO in day-ahead scheduling. Suppose scenario k happens in real time. The produced wind power in real time, Q_{w_k}, is different from the scheduled wind power, Q_{sw} in day-ahead market. It is assumed that the balancing utility and the WPP have contracts with the ISO in the strategic schemes. Based on these contracts, if the WPP produces greater than its scheduled power in the day-ahead market, the balancing utility reduces its generation power by $(Q_{w_k} - Q_{sw})$ and pays f_{up} to the WPP for every MWh that the WPP produces for balancing utility. f_{up} is called positive balancing price and is less than the MCP. If the WPP produces less than its scheduled power, the balancing utility increases its generation power by $(Q_{w_k} - Q_{sw})$ and receives f_{down} from the WPP for every MWh that balancing utility produces for the WPP. f_{down} is called negative balancing price and is greater than the MCP. This can be considered as a penalty mechanism for the WPP to force it to improve its wind power estimations. The balancing cost for the WPP is defined as follows:

$$blnccost_k = \begin{cases} f_{up}(Q_{sw} - Q_{w_k}) & Q_{w_k} > Q_{sw} \\ f_{down}(Q_{sw} - Q_{w_k}) & Q_{w_k} < Q_{sw} \end{cases} \quad (10)$$

A. The WPP Behaves as a Non-Strategic Price-Taker Producer

This scheme is referred to as *PT scheme*. In this scheme, the WPP does not behave strategically and receives market price for producing every MWh energy. Hence, the WPP can be considered as a negative load in the SFE modeling. Therefore, SFE can be modeled by replacing Q_{D0} with $Q_{D0} - Q_{w_{exp}}$ in (7)–(9). Where $Q_{w_{exp}}$, is the expected value of wind power over different scenarios.

B. The WPP Sets Its Generation as a Strategic Producer

This scheme is referred to as *GP scheme*. In this scheme, the WPP takes part in the day-ahead market as a strategic market player by submitting to the ISO the value of generation power that it is willing to produce. It is assumed that the ISO accepts the whole proposed generation power of the WPP. Other generating firms bid their supply functions to the ISO. The SFE model under the GP scheme is presented in Appendix B [14].

Study of this scheme in [9] and [19] showed that it may not lead to increase of competition since generation power of WPPs is intermittent. Hence, two other schemes are proposed and compared with the GP scheme in this paper.

C. The WPP Sets Its Supply Function as a Strategic Producer

This scheme is referred to as *SF scheme*. In this scheme, the WPP takes part in the day-ahead market as a strategic market player by submitting a supply function to the ISO. The SFE model under the SF scheme is presented in Appendix C [15].

D. The WPP Joins a NGF and the Aggregated Firm Sets Its Supply Function as a Strategic Producer

In this scheme, the WPP teams up with a NGF and the aggregated firm participates in electricity market as a single firm. This single firm is referred to as *WN firm* and this scheme is referred to as *WN scheme*. The WN firm submits a linear supply function to the ISO. The slope of its supply function is equal to slope of marginal cost of the joined NGF and its intercept is determined such that the profit of the WN firm is maximized. The goal of the coalitions here is to reduce the WPP's balancing cost, omit uncertainty from electricity market, and reduce the necessary regulating reserves. The expected profit of the WN firm is equal to:

$$\bar{\pi}_{wn} = \sum_{k \in K} p_k \pi_{wn_k} \tag{11}$$

where π_{wn_k} is the profit of the WN firm at scenario k. Suppose Q_{swn} is scheduled power of the WN firm in day ahead market, $\bar{Q}_{w_k}$ is the maximum power of the WPP at scenario k without wind power spillage, Q_{n_k} is generation power of the joined NGF at scenario k and $Q_{n_{max}}$ is the maximum capacity of the joined NGF. In this scheme, it is assumed that if the WN firm overestimates its generation capability and it is dispatched in day-ahead market more than its generation capability in real time, it is charged for balancing cost. However, if the WN firm underestimates its generation capability and it is dispatched in day-ahead market less than its generation capability, its excess generation will be spilled. Therefore, It is assumed that 1) if $Q_{swn} \leq \bar{Q}_{w_k}$, wind power is spilt so that $Q_{w_k} = Q_{swn}$ and $Q_{n_k} = 0$, 2) if $\bar{Q}_{w_k} < Q_{swn} \leq Q_{n_{max}} + \bar{Q}_{w_k}$ wind power is not split i.e., $Q_{w_k} = \bar{Q}_{w_k}$ and $Q_{n_k} = Q_{swn} - \bar{Q}_{w_k}$, and 3) if $Q_{swn} > Q_{n_{max}} + \bar{Q}_{w_k}$, $Q_{w_k} = \bar{Q}_{w_k}$, $Q_{n_k} = Q_{n_{max}}$, and the WN firm is charged with balancing cost for $Q_{swn} - Q_{n_{max}} - Q_{w_k}$. Suppose that K_1, K_2, and K_3 are sets of scenarios in which $Q_{swn} \leq \bar{Q}_{w_k}$, $\bar{Q}_{w_k} < Q_{swn} \leq Q_{n_{max}} + \bar{Q}_{w_k}$, and $Q_{swn} > Q_{n_{max}} + \bar{Q}_{w_k}$, respectively. π_{wn_k} is equal to:

$$\pi_{wn_k} = \lambda Q_{swn} \qquad \forall k \in K_1 \tag{12}$$

$$\pi_{wn_k} = \lambda Q_{swn} - \left(a_n (Q_{swn} - Q_{w_k}) + \frac{1}{2} b_n \left(Q_{swn} - Q_{w_k}\right)^2\right) \qquad \forall k \in K_2 \tag{13}$$

$$\pi_{wn_k} = \lambda Q_{swn} - \left(a_n Q_{n_{max}} + \frac{1}{2} b_n Q_{n_{max}}^2\right) - f_{down}\left(Q_{swn} - Q_{n_{max}} - Q_{w_k}\right) \qquad \forall k \in K_3 \tag{14}$$

Using step function the expected profit of the WN firm can be formulated as below:

$$\bar{\pi}_{wn} = \sum_{k \in K} p_k \left(\lambda Q_{swn} - \left(a_{wn_k} Q_{swn} + \frac{1}{2} b_{wn_k} Q_{swn}^2\right)\right) + C \tag{15}$$

where $b_{wn_k} = a_{wn_k} = 0 \ \forall k \in K_1$, $b_{wn_k} = b_n$ and $a_{wn_k} = a_n - b_n Q_{w_k} \ \forall k \in K_2$, and $b_{wn_k} = 0$ and $a_{wn_k} = f_{down} \ \forall k \in K_3$. Parameters a_{wn_k} and b_{wn_k} and C can be written as below:

$$a_{wn_k} = (a_n - b_n Q_{w_k})\, u\left(Q_{swn} - Q_{w_k}\right) u\left(Q_{n_{max}} + Q_{w_k} - Q_{swn}\right) + f_{down} u\left(Q_{swn} - Q_{n_{max}} - Q_{w_k}\right) \tag{16}$$

$$b_{wn_k} = b_n u\left(Q_{swn} - Q_{w_k}\right) u\left(Q_{n_{max}} + Q_{w_k} - Q_{swn}\right) \tag{17}$$

$$C = \sum_{k \in K} p_k \left(\left(a_n Q_{w_k} - \frac{1}{2} b_n Q_{w_k}^2\right) u\left(Q_{swn} - Q_{w_k}\right) u\left(Q_{n_{max}} + Q_{w_k} - Q_{swn}\right) + \left(f_{down}(Q_{n_{max}} + Q_{w_k}) - \left(a_n Q_{n_{max}} + \frac{1}{2} b_n Q_{n_{max}}^2\right)\right) u\left(Q_{swn} - Q_{n_{max}} - Q_{w_k}\right)\right) \tag{18}$$

Using (15), the WN firm can be considered as other NGFs. Note that both parameters a_{wn_k} and b_{wn_k} change in different scenarios. However, the slope of bid function of the WN firm is constant and equal to b_n. To complete the model, matrices $\boldsymbol{Q_f}$, $\boldsymbol{R_f}$, and $\boldsymbol{R'_f}$, for other firms, can be calculated using formulas given in Appendix A assuming $b_{wn} = b_n$. For the WN firm, matrices $\boldsymbol{Q_{wn}}$, $\boldsymbol{R_{wn}}$, and $\boldsymbol{R'_{wn}}$ are defined for each subset of scenarios, i.e., for K_1, K_2, and K_3 using formulas given in Appendix A considering (16) and (17). Let use subscript j to denote these subsets. Hence, matrices $\boldsymbol{Q_{wn_j}}$, $\boldsymbol{R_{wn_j}}$, and $\boldsymbol{R'_{wn_j}}$ are defined for $j = 1, 2, 3$. Moreover, since a_{wn} and consequently $\boldsymbol{R_{wn_2}}$ have different values in different scenarios k in K_2 (see (28) and (31) in Appendix A), subscript k is used for $\boldsymbol{R_{wn_2}}$ and it is shown as $\boldsymbol{R_{wn_{2_k}}}$.

Considering above-mentioned definitions and Appendix A, (7)–(9) can be rewritten as the following equations:

$$\sum_{k \in K_1} p_k(\boldsymbol{H_1}(\boldsymbol{\alpha} + \boldsymbol{\mu}) + \boldsymbol{R_1} + \boldsymbol{R'_1} Q_{D0}) + \sum_{k \in K_2} p_k(\boldsymbol{H_2}(\boldsymbol{\alpha} + \boldsymbol{\mu}) + \boldsymbol{R_{2_k}} + \boldsymbol{R'_2} Q_{D0}) + \sum_{k \in K_3} p_k(\boldsymbol{H_3}(\boldsymbol{\alpha} + \boldsymbol{\mu}) + \boldsymbol{R_3} + \boldsymbol{R'_3} Q_{D0}) - \boldsymbol{U}\boldsymbol{\mu} = 0 \tag{19}$$

$$\boldsymbol{V} Q_{D0} + \boldsymbol{U}(\boldsymbol{\alpha} + \boldsymbol{\mu}) \leq \boldsymbol{Q_s^{max}} \quad \perp \quad \boldsymbol{\mu^{max}} \tag{20}$$

$$\boldsymbol{V} Q_{D0} + \boldsymbol{U}(\boldsymbol{\alpha} + \boldsymbol{\mu}) \leq \boldsymbol{0} \quad \perp \quad \boldsymbol{\mu^{min}} \tag{21}$$

The SFE is computed by solving (19)–(21) using the proposed algorithm in [18]. Solving this model is more straightforward and easier than solving all KKT conditions of the bi-level optimizations of generating firms.

Considering transmission constraints in the equilibrium model does not lead to a straightforward model like the one presented in (19)–(21). However, considering transmission constraints is not a complicated issue. To model transmission network, DC power flow equations and line flow limits are added to the ISO's optimization, i.e., (1)–(3), as constraints. KKT conditions of the ISO's optimization are considered as constraints in the optimization of each power producer given in (4)–(5). Solving the KKT conditions of optimization problems of all power producers gives the equilibrium point.

IV. Uncertainty Modeling

In this section the medium-term study horizon is modeled using two different approaches called *single and multi-equilibrium approaches*.

A. Single-Equilibrium Approach

In this approach, it is assumed that the only available information about wind generation is the PDF of wind speed over the study period. Based on the PDF of wind speed in study horizon and wind turbines power curves, wind power generation is modeled by a set of scenarios. These scenarios cover the whole range of wind power generation and are referred to as *medium-term scenarios*. Market equilibrium is computed assuming the WPP maximizes its expected profit over medium-term scenarios. In this approach one market equilibrium is computed for the whole medium-term horizon. This approach is referred to as *single- equilibrium approach*. In more detail, after determining medium-term scenarios, SFE under the WN scheme is computed using (19)–(21). SFE under the GP and SF schemes can be computed using (7)–(9). Parameter of (7)–(9) of the GP and SF schemes can be computed using the formulas given Appendices B and C respectively.

B. Multi-Equilibrium Approach

In practice, power producers change their bids every day. Power producers use wind power forecasts to determine their bids accurately. In medium term study, wind power forecasts are not available. However, if historic data of wind power forecast is available, market equilibrium and consequently behavior of power producers can be modeled more accurately. Assume wind power historic forecasts are available. In other words, assume that PDFs of error of wind power forecast are available. In this approach, it is assumed that every medium-term scenario is realized considering its probability. The wind power of each medium-term scenario is considered as the forecasted value for wind power. Forecasts of wind power have error levels that may vary depending on forecast horizon. Based on the historic data of wind power forecast, a Normal PDF is assigned to wind power generation of every medium-term scenario considering wind generation level and time duration between forecasting and operation [5]. Some scenarios are defined around each medium-term scenario based on the associated Normal PDF of wind power in short-term. These scenarios are referred to as *short-term scenarios*. Market equilibrium is computed for each medium-term scenario assuming the WPP maximizes its profit over the associated short-term scenarios. In this approach, one market equilibrium is computed for each medium-term scenario. This approach is referred to as *multi-equilibrium approach*. More specifically, after computing short-term scenarios for each medium-term scenario, SFE under the WN scheme is computed for each medium-term scenario using (19)–(21). Under the GP and SF schemes, SFE can be computed using (7)–(9). In this approach, after computing SFE for each medium-term scenario, expected value of each market variable over all medium-term scenarios is computed.

V. Numerical Simulations

In this section, the proposed schemes for strategic bidding of the WPP are applied to a 100-generator test system. The test system consists of 6 NGFs with a uniform electricity market. NGFs 1 to 6 have 28, 16, 8, 18, 15, and 15 generating units respectively. The marginal cost function of each NGF is computed by aggregating the marginal cost functions of its generating units. A linear marginal cost is fitted to the aggregated marginal cost of each NGF. Parameters of the aggregated marginal cost functions of the NGFs and their generation limits are given in Table I. Each NGF offers a linear supply function to the ISO. The total demand of the market is 20 GW. Suppose a WPP with the capacity of 4 GW is added to the system, which leads to a wind penetration of 15.68%. It is assumed that wind speed at the WPP site has a Weibull distribution with scale parameter equal to 10 m/s and shape parameter equal to 1.8. It is also assumed that the WPP has an overall turbine power curve as presented in Fig. 1. Transmission constraints and price elasticity of load are ignored here to avoid the impacts of transmission congestion and load elasticity on the results and assess the pure impacts of strategic behavior of the WPP. The impacts of transmission constraints, price elasticity of load, and other parameters that may affect the result are assessed in Section V.C. The GAMS mathematical programming platform and the PATH solver was used to solve the presented model in (19)–(21).

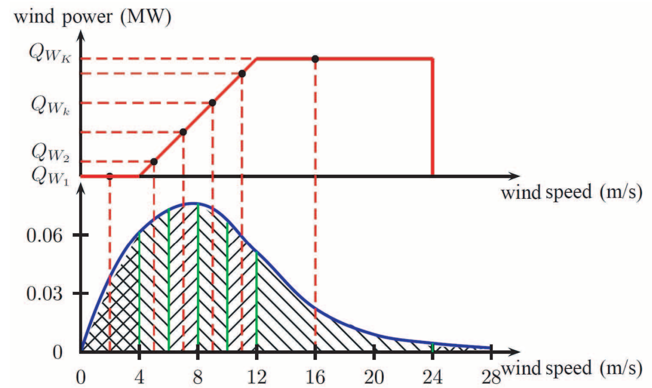

Fig. 1. Sampling wind power.

TABLE I
Parameters of NGFs

Firms:	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
a ($\$/MWh$)	16	10.8	5.6	26	20	24
b ($\$/MW^2h$)	0.007	0.011	0.026	0.005	0.017	0.017
Q_s^{max} (MW)	5500	4500	3000	5500	3500	3500

A. Single-Equilibrium Approach

In this section, the impacts of strategic bidding of the WPP in medium-term are studied assuming the only available information about the wind is the PDF of wind speed over the study horizon. In order to define medium-term scenarios, a simple sampling method using PDF of the wind speed and the wind turbine power curve is presented in Fig. 1. In order to have n_s medium-term wind power scenarios, or n_s wind power samples, one sample is taken from the zero power section of wind turbine power curve, one from the maximum wind power, and $n_s - 2$ samples between these two values. The probability of each medium-term scenario is computed using wind speed PDF. In Fig. 1, the probability of each medium-term scenario is specified with the related hatched area. Based on the sampling method, 20 discrete values for wind power generation and the associated possibilities are determined for medium-term scenarios. In this study, positive and negative balancing prices are adopted from [20]. Based on [20], $f_{up} = (1-\tau)MCP$ and $f_{down} = (1+\tau)MCP$. In determining balancing prices it is assumed that MCP is constant and equal to the MCP of the PT scheme. Different values are assumed for τ in the available literature (e.g., 0.2 in [21] and 0.9 in [22]). In this paper it is assumed that $\tau = 0.5$.

MCP, profit of the WPP, profit of NGF 6 that joins the WPP in the WN scheme, total balancing cost, and consumer price for the proposed schemes are given in Table II. For the WN scheme, sum of profits of the WPP and NGF 6 is given in Table II. In the PT scheme the WPP is considered as a negative load and balancing cost is paid by consumers. Since in the PT scheme

TABLE II
SIMULATION RESULTS OF SINGLE-EQUILIBRIUM APPROACH

	Schemes			
	PT	GP	SF	WN
MCP ($\$/MWh$)	59.60	58.34	56.90	57.59
WPP's dispatched power (GW)	-	1.67	1.01	3.76
Expected profit of WPP($k\$/h$)	118.10	77.90	73	127.80
Profit of NGF 6 ($k\$/h$)	31.90	33.60	31	
Total balancing cost ($k\$/h$)	42	19.50	-15.60	4.60
Wind support cost ($k\$/h$)	0	40.20	45.20	22.20
Consumer price ($\$/MWh$)	59.60	60.35	59.16	58.70

TABLE III
SIMULATION RESULTS OF MULTI-EQUILIBRIUM APPROACH

	Schemes			
Expected value of:	PT	GP	SF	WN
MCP ($\$/MWh$)	58.75	57.90	57.24	58.10
WPP's dispatched power (GW)	-	1.87	1.34	3.54
Expected profit of WPP($k\$/h$)	112.80	92.40	86.20	139
Profit of NGF 6 ($k\$/h$)	32.20	31.86	31.60	
Balancing cost ($k\$/h$)	24.80	1.33	-10.70	0.18
Wind support cost ($k\$/h$)	0	20.40	26.60	6
Consumer price ($\$/MWh$)	58.75	58.92	58.57	58.40

balancing cost is not taken into account in the WPP's cost function, whereas it is considered in the cost function of the WPP in strategic schemes, the computed MCP from social welfare optimization does not include the balancing cost in the PT scheme despite the strategic schemes. For the sake of fair comparison, in the PT scheme balancing cost is prorated to total consumption and is added to the MCP. This modified price is considered as MCP in the PT scheme.

In Table II, comparison of the MCP for different schemes shows that the MCP of every strategic scheme is less than the MCP of the PT scheme. The SF scheme has the least MCP among the strategic schemes. The reason is increase of competition in the SF scheme due to increase of number of competitors. The GP scheme has the highest MCP among strategic schemes. The reason is that the control variable of the WPP in the GP scheme, i.e., its generation power, is uncertain and consequently its strategic behavior does not increase the competition as well as other strategic schemes. MCP in the WN scheme is heigher than the MCP in the SF scheme. The reason is that although the WPP has strategic behavior in the WN scheme, number of competitors in the WN scheme is less than number of competitors in the SF scheme.

As Table II shows profits of the WPP in every strategic scheme is less than its profit in the non-strategic scheme due to paying balancing cost in the strategic schemes. Hence, the WPP is reluctant to participate in the strategic schemes. In order to encourage the WPP to participate in the strategic scheme, a supporting tariff is defined for the WPP to be compensated for its loss in the strategic schemes in comparison to the PT scheme. According to this supporting tariff, in a strategic scheme, the difference between the profit of the WPP in the PT scheme and the strategic scheme is paid to the WPP by consumers. This value is referred to as *wind support cost*. In the WN scheme, the supporting tariff is applied to the aggregated WPP and NGF firm. Considering this supporting tariff, consumer price is computed by prorating wind support cost to total consumption and adding it to the MCP. In the PT scheme, supporting tariff is zero and consequently consumer price is equal to the MCP. Based on Table II, wind support cost in the WN scheme is less than other strategic schemes which indicates strategic behavior of the WPP through the WN scheme leads to the least reduction in its profit in comparison to other strategic schemes. Hence, consumer prices in the WN scheme are less than other schemes, as shown in Table II.

Comparison of the balancing costs for different schemes in Table II shows that strategic behavior of the WPP decreases the absolute value of balancing cost and consequently the required regulating reserve especially in the WN scheme. In strategic schemes the WPP is responsible to pay for balancing cost. Strategic behavior of the WPP with the purpose of increasing its profit leads to decrease of balancing cost. In the WN scheme, NGF 6 covers the power imbalance of the WPP as much as possible and the aggregated firm is charged for rest of the imbalance. This is why the absolute value of the balancing cost in the WN scheme is considerably less than other schemes. In the SF scheme the balancing cost is negative. This means the optimal strategy of the WPP is to withdraw generation from day-ahead market by increasing the intercept of its supply function and selling the extra power with balancing price. Selling the extra power with the balancing price leads to negative balancing cost.

In conclusion, strategic behavior of the WPP leads to decrease in the MCP, decrease in absolute value of balancing costs, and consequently decrease in required regulating reserve in all strategic schemes. It also leads to decrease in consumer price in the SF and WN schemes even after charging consumers for wind supporting tariff. Strategic behavior of the WPP in the WN scheme leads to the lowest consumer prices and the least required regulating reserve.

Using the proposed supporting tariff for the WPP is not easy in practice due to its complexity. In practice, supporting tariff could be defined based on the annual forecast of the WPP's profit in the PT scheme.

The WN scheme was applied to the IEEE 30-bus and IEEE 118-bus test systems. Similar results were extracted from those case studies.

B. Multi-Equilibrium Approach

In this section, strategic bidding of the WPP is studied in a medium-term horizon considering historic data of wind power forecast. The 20 samples of wind power generation, which were selected as medium-term scenarios in Section V.A, are considered as wind power forecasts, and short-term scenarios are defined for each medium-term scenario. Market equilibrium is computed for each medium-term scenario and the expected value of each variable over medium-term scenarios is computed. Simulation results are given in Table III. Simulation result of multi-equilibrium approach confirms the simulation result of single-equilibrium approach, i.e., Table III confirms that strategic behavior of the WPP decreases the MCP and the absolute value of balancing cost in comparison to the PT scheme.

When historic data of wind power forecast are taken into account, the uncertainty reduces considerably. Hence, the defect of the GP scheme, which was uncertainty in control variable, is improved. Moreover, when uncertainty drops, the WN firm behaves more like a coalition and leads to increase of the MCP. This is why the MCP for the GP scheme is less than the MCP for the WN scheme in multi-equilibrium approach.

Table III shows that strategic behavior of the WPP in the WN scheme leads to the least supporting tariff and consequently least consumer price in comparison to other strategic schemes.

It also leads to the least absolute value of balancing costs and consequently least level of required regulating reserve. Comparison of Tables II and III shows that lower uncertainty leads to decrease in supporting cost, consumer price, and absolute value of balancing cost and consequently the required regulating reserve in all strategic schemes. Comparison of Tables II and III also shows that as the uncertainty reduces, the proposed schemes converge to similar outcomes.

It should be mentioned that although the price difference between every two schemes is not significant, the differences between the associated annual profits are significant. For example, consider the SF and WN schemes in Table III. These two schemes are similar, and the difference between their consumer price is \$0.17/MWh or 0.29%. MCP difference between these two schemes is \$0.86/MWh. Suppose this price difference lasts for 10 hours per day, and assume that only 65% of firm 1 is committed, on average, in these hours. Then firm 1 will gain M\$11.2/year more in the WN scheme than in the SF scheme. If the uncertainties that are not modeled reduce the profit difference to 50% of the computed value, firm 1 will gain M\$5.6/year extra in the WN scheme than in the SF scheme, which is still significant.

C. Impacts of Other Parameters

In this section, the impacts of parameters that may affect the study are assessed. To keep the discussion concise, this section focuses on the WN scheme and single-equilibrium approach.

1) Balancing Prices: In order to assess the impacts of balancing prices, the consumer prices and the supporting costs are plotted against τ in Figs. 2 and 3 for the PT and WN schemes assuming different capacities for NGF 6. As Fig. 2 shows, higher values of τ leads to the increase of consumer price in the PT scheme due to the increase of balancing costs. As τ increases, the WN firm withdraws its generation power from day-ahead market to avoid paying expensive balancing cost in real time. This leads to the dispatch of more expensive generators in day-ahead market, and consequently MCP and consumer price increases, as demonstrated in Fig. 2. In addition, increasing τ increases the balancing cost and decreases the power of the WN firm, which leads to decrease of its profit despite of increase in MCP. Decreasing the profit of the WN firm causes an increase in the supporting cost and the consumer price, as it is shown in Figs. 2 and 3. The optimal value of τ depends on the costs of balancing units and the market policies for penalizing WPPs to control the uncertainty level. This would also impact the level of required regulating reserves, which is beyond the scope of this paper.

2) Teaming up With Different NGFs: In order to determine which partnership leads to minimum consumer price, we have investigated all possible coalitions between the WPP and every NGF of Table I separately. It is assumed that the NGF partner has an unlimited capacity and $\tau = 0.5$. Simulation results are presented in Table IV.

In real-time, the WPP's partner should reduce its generation power during the times that wind power generation is higher than the forecasted value to avoid spilling wind energy. A low marginal cost NGF partner loses more than a high marginal cost NGF partner when reduces its generation power. Therefore, paring with the higher marginal cost NGF leads to the lower MCP and consequently the lower consumer price. Note that marginal cost of a firm depends on its generation power.

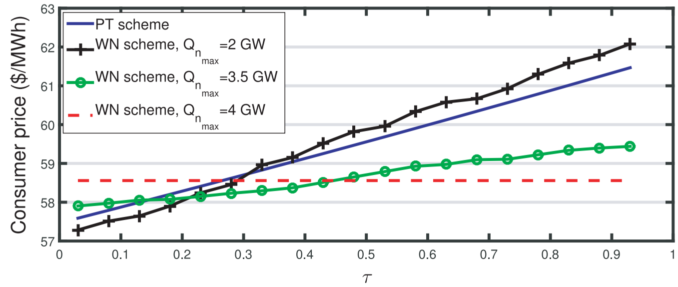

Fig. 2. Consumer price versus τ.

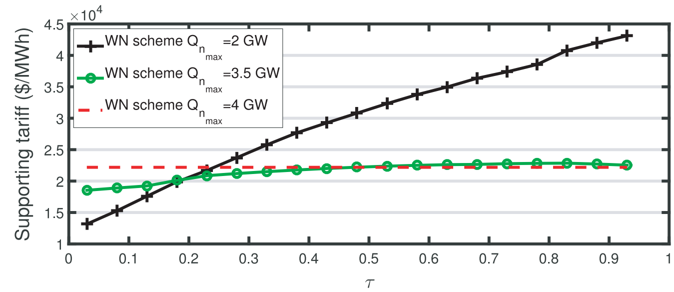

Fig. 3. Supporting tariff cost versus τ.

TABLE IV
SIMULATION RESULTS WHEN THE WPP PAIRS WITH DIFFERENT NGFS

	Joined NGF with the WPP					
	NGF 1	NGF 2	NGF 3	NGF 4	NGF 5	NGF 6
MCP ($\$/MWh$)	58.55	58.22	57.90	59.01	57.64	57.44
Profit of WPP ($k\$/h$)	120.2	119.5	115.7	121.2	118.3	115.3
Profit of joined NGF ($k\$/h$)	104.40	88.50	24.50	81.40	21.10	12.50
Profit of joined NGF in PT scheme ($k\$/h$)	113	101.10	52.50	87.80	41.40	31.90
Total payment to firms ($k\$/h$)	1171	1164	1158	1180	1152	1149
Wind support cost ($k\$/h$)	6.40	11.14	30.68	3.26	19.97	22.20
Consumer price ($\$/MWh$)	58.87	58.77	59.43	59.17	58.63	58.56

TABLE V
SENSITIVITY ANALYSIS OF CONSUMER PRICE VERSUS VARIATIONS OF MARGINAL COSTS IN THE PT AND WN SCHEMES

		Variations of a		Variations of b	
		+5%	-5%	+5%	-5%
PT	Δ(Consumer price) (%)	+0.015	-0.016	+0.032	-0.033
	Consumer price	60.18	58.33	61.21	57.31
WN	Δ(Consumer price) (%)	+0.015	-0.015	+0.032	-0.032
	Consumer price	59.59	57.87	60.62	56.84

In this case study, firms 5 and 6 have higher marginal costs in their operating points in comparison with other firms. Therefore, as Table IV shows, the market has the lower MCP and consequently the lower consumer price when the WPP pairs with firm 5 or 6 in comparison to other firms.

3) Operation Cost: A sensitivity analysis is performed to determine the sensitivity of simulation results to the parameters of the marginal cost functions. To this end, all parameters a are increased by 5% while other parameters are constant, and simulation results are computed for the PT and WN schemes. The process is repeated for decreasing all parameters a by 5%, increasing all parameters b by 5%, and decreasing all parameters b by 5% while other parameters are kept constant. Simulation results of the sensitivity analysis are given in Table V. As Table V shows, in all above-mentioned changes consumer price in the WN scheme remains less than consumer price in the PT scheme, i.e., the results are not sensitive to the parameters of operation costs.

TABLE VI
SIMULATION RESULTS FOR DIFFERENT LOAD LEVELS

	Off-peak load		Medium load		Peak load	
	PT	WN	PT	WN	PT	WN
MCP ($\$/MWh$)	40.50	38.30	51.05	48.92	59.60	57.59
Q_{wn} (GW)	-	2.62	-	3.44	-	3.76
Profit of WPP & NGF 6($k\$/h$)	83.40	57.22	117.70	93.40	150	127.80
Balancing cost ($k\$/h$)	28.40	0	35.80	0	42	4.60
Wind support cost ($k\$/h$)	0	25.18	0	24.30	0	22.20
Consumer price ($\$/MWh$)	40.50	40.68	51.05	50.40	59.60	58.70

TABLE VII
SIMULATION RESULTS CONSIDERING ELASTICITY OF LOAD

	Inelastic load		Elastic load	
	PT	WN	PT	WN
MCP ($\$/MWh$)	59.60	57.59	59.60	57.39
Total demand (GW)	20	20	19.60	22.20
Q_{wn} (GW)	-	3.76	-	4
Profit of WPP & NGF 6($k\$/h$)	150	127.80	150	129
Balancing cost ($k\$/h$)	42	4.60	42	9.70
Wind support cost ($k\$/h$)	-	22.20	-	21
Consumer price ($\$/MWh$)	59.60	58.70	59.60	58.33

TABLE VIII
SIMULATION RESULTS CONSIDERING LOAD UNCERTAINTY

	$\sigma = 500MW$		$\sigma = 1500MW$	
Expected value of:	PT	WN	PT	WN
MCP ($\$/MWh$)	59.66	57.60	62.32	57.63
Balancing cost ($k\$/h$)	42	4.60	42	4.60
Wind support cost ($\$/MWh$)	-	32.87	-	22.60
Consumer price ($k\$/h$)	59.66	58.73	62.32	59.28

TABLE IX
CONSUMER PRICE CONSIDERING TRANSMISSION CONSTRAINTS

		Consumer price ($\$/MWh$)			
NGFs in	Capacity	PT scheme		WN scheme	
area 1	of tie-lines	Area 1	Area 2	Area 1	Area 2
NGF 1	0.5 GW	62.08	81.33	62.08	82.57
NGF 2	1 GW	66.50	79.20	66.50	79.90
NGF 3	0.5 GW	84.44	73.66	84.44	73.88
NGF 4	1 GW	76.81	76	76.81	75.84
NGF 3	0.5 GW	108	61.06	108	60.29
NGF 5	1 GW	97	62.42	97	61.62

4) Load Level: In order to assess the impacts of load level, the study is performed for a peak load, medium load, and off-peak load, and the results are compared. In this study it is assumed that medium load is equal to 16 GW, peak load is 125% of medium load (20 GW) and off-peak load is about 70% of medium-load (11 GW) [23]. Simulation results are given in Table VI. Table VI shows that although at peak load and medium load consumer prices in the WN scheme are \$0.9/MWh and \$0.65/MWh less than consumer price in the PT scheme, at off-peak load consumer price in the WN scheme is \$0.18/MWh greater than consumer price in the PT scheme. This means although the WN scheme in medium load and peak load is efficient, it loses its efficiency in off-peak load.

5) Price Elasticity of Load: Price elasticity of load has been considered in the modeling through c_i and d_i in (1). To assess the impacts of price elasticity of load, it is assumed that we have a load with $c = \$64/\text{MWh}$ and $d = \$0.0003/\text{MW}^2\text{h}$ which leads to elasticity of 0.1 around operating point, i.e., $|\Delta\rho/\rho|/|\Delta Q_D/Q_D| = 0.1$, which is reasonable in electricity markets. The parameters of the elastic load are selected so that consumer price remains constant in the PT scheme. Simulation results for the inelastic and elastic loads are given in Table VII. Table VII shows that in the case that load is elastic in comparison to the case that load is inelastic, MCP in the WN scheme minus MCP in the PT scheme decreases by \$0.2/MWh, dispatched power of the WN firm increases by 0.24 GW, total consumption increases by 2.2 GW, and consumer price in the WN scheme minus consumer price in the PT scheme decreases by \$0.37/MWh. This means that the WN scheme is more effective in the presence of elastic loads than inelastic loads.

6) Load Uncertainty: In order to take demand uncertainty into account, first some scenarios for demand are defined based on the PDF of demand. Suppose N scenarios are defined for possible values of load in the study horizon. Then, N load scenarios and M wind power generation scenarios are combined and $N.M$ wind-demand scenarios are defined and their associated probabilities are computed. Market equilibrium for WN scheme is computed using (19)–(21) by replacing parameter Q_{D0} with Q_{Dk}. The same process can be used for other schemes. Suppose load has a Normal PDF with average 20 GW. Simulation results for the PT and WN schemes assuming standard deviation of load is equal to 1.5 GW and 0.5 GW are given in Table VIII. Simulation result shows that the MCP, balancing cost, and consequently consumer price decrease in the WN scheme in comparison to the PT scheme. Therefore, performance of the WN scheme remains better than performance of the PT scheme under demand uncertainty.

7) Transmission Constraints: In this study it is assumed that we have a two area network. Area 1 has a 5 GW load and area 2 has a 15 GW load. The two areas are connected through four parallel tie-lines. Two scenarios for total transmission capacity and three different combinations for locations of the NGFs in areas 1 and 2 are considered. The NGFs that are located in area 1 and total capacity of tie-lines are given in columns 1 and 2 of Table IX. The WPP and the NGFs that are not shown in column 1 are located in area 2. Consumer price of each area is computed by prorating supporting cost to all consumption and adding it to its locational marginal price. Consumer price for different tie-lines capacities and different combinations for locations of the NGFs in areas 1 and 2 are given in Table IX. As Table IX shows, if transmission constraints are taken into account, consumer price of area 2 in the WN scheme can be lower or higher than the consumer price of area 2 in the PT scheme; this depends on the locations of NGFs in area of 1 and 2 and total capacity of tie-lines. In the considered capacities for tie-lines and the considered combinations for NGFs in area 1 and 2, the consumer price of area 1 does not depend on the selected scheme as it is shown in Table IX. Hence, when transmission constraints are modeled, the performance of the WN scheme in comparison to the PT scheme depends on the location of congestion and its intensity.

VI. CONCLUSION

In this paper, the impacts of strategic bidding of a WPP on an electricity market are studied. To this end, three schemes for the strategic bidding of the WPP are compared at market's Nash equilibrium. The simulation results show that the strategic bidding of the WPP in the SF and WN schemes reduces the MCP in comparison to the PT scheme. Strategic bidding of the WPP reduces its profit in all schemes. To encourage the WPP to participate in the market strategically, a wind support tariff is defined to keep its profit equal to its profit in the PT scheme. Consumers are assumed to be responsible for paying the costs of the wind support tariff. The simulation results show that even after considering the wind support tariff for the WPP, strategic bidding of the WPP reduces the costs of the consumers in the SF and WN schemes. The results also show that the WN scheme is the best scheme from the viewpoint of increasing competition and deceasing consumers' price. Considering historic data of wind generation forecasting confirms the extracted results. Simulation results show that the efficiency of the WN scheme decreases in off-peak load, increases under elastic loads, and it depends to the location and intensity of congestion in congested networks.

Determining the optimal values of balancing prices and the impacts of strategic behavior of WPPs on the short-term operation of power systems are future directions of this research work.

Appendix

A. Appendix A—Parameters of the SFE Model

KKT conditions of ISO optimization, i.e., (1)–(3), lead to:

$$\lambda = \alpha_f + b_f Q_{sf} = c_j - d_j Q_{Dj} \tag{22}$$

$$Q_{sf} = v_f + \boldsymbol{u_f^T} \boldsymbol{\alpha} \tag{23}$$

where

$$u_{f_j} = \frac{1}{b_f b_j B}, \quad u_{f_f} = \frac{-b_f B - 1}{b_f^2 B}, \quad v_f = \frac{1}{b_f B} \tag{24}$$

$$B = \begin{cases} \sum_{i \in F} \frac{1}{b_i} & elastic\ load \\ \sum_{i \in F} \frac{1}{b_i} + \sum_{j \in D} \frac{1}{d_j} & inelastic\ load \end{cases} \tag{25}$$

substituting (22) and (23) in (4) and rearranging it yield (6). The elements of $n_g \times n_g$ matrix $\boldsymbol{Q_f}$, $n_g \times 1$ vectors $\boldsymbol{R_f}$ and $\boldsymbol{R'_f}$, and scalars S'_f, S''_f and Q_{D0} are defined as follows:

$$Q_{f_{ij}} = \frac{B_f + B_{Q_{ij}}}{2B^2 b_i b_j} \quad B_f = \frac{1}{b_f} \quad C_f = \frac{a_f}{b_f} \tag{26}$$

$$B_{Q_{ij}} = \begin{cases} 0 & i \neq f, \quad j \neq f \\ B^2 b_i & i = j = f \\ -B & i = f, \quad j \neq f \\ B & i \neq f, \quad j = f \end{cases}, \forall i, j \in F \tag{27}$$

$$R_{f_i} = \begin{cases} -v_i (C_f - a_i B) & i = f \\ -v_i C_f & i \neq f \end{cases}, \forall i \in F \tag{28}$$

$$R'_{f_i} = \frac{B_f}{B^2 b_i} \quad \forall i \in F, \quad S'_f = \frac{-C_f}{B} \quad S''_f = \frac{B_f}{2B^2} \tag{29}$$

$$Q_{D0} = \begin{cases} \sum_{j \in D} \frac{c_j}{d_j} & elastic\ load \\ total\ demand & inelastic\ load \end{cases} \tag{30}$$

The elements of $n_g \times 1$ vectors $\boldsymbol{\alpha}$, $\boldsymbol{R}$, $\boldsymbol{R'}$, and $n_g \times n_g$ matrix $\boldsymbol{H}$, are defined as follows:

$$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_{n_g} \end{pmatrix}, \boldsymbol{R} = \begin{pmatrix} R_{1_1} \\ R_{2_2} \\ \vdots \\ R_{n_{g_{n_g}}} \end{pmatrix}, \boldsymbol{R'} = \begin{pmatrix} R'_{1_1} \\ R'_{2_2} \\ \vdots \\ R'_{n_{g_{n_g}}} \end{pmatrix} \tag{31}$$

$$\boldsymbol{H} = \begin{pmatrix} 2Q_{1_{1,1}} & Q'_{1_{1,2}} & \cdots & Q'_{1_{1,n_g}} \\ Q'_{2_{21}} & 2Q_{2_{22}} & \cdots & Q'_{2_{2,n_g}} \\ \vdots & \vdots & \vdots & \vdots \\ Q'_{n_{g_{n_g,1}}} & Q'_{n_{g_{n_g,2}}} & \cdots & 2Q_{n_{g_{n_g,n_g}}} \end{pmatrix} \tag{32}$$

$$Q'_{f_{fg}} = Q_{f_{fg}} + Q^T_{f_{gf}} \tag{33}$$

V is a vector that its fth element is equal to v_f, U is a matrix that its fth row is equal to u_f^T.

B. Appendix B: SFE Model for the GP Scheme

In this scheme, the WPP bids its generation power to the ISO. The ISO accepts the whole generation power that is offered by the WPP. Other firms bid their supply functions to the ISO. Hence, assuming Q_{sw} is dispatched power of the WPP by the ISO, the decision variable vector is $\boldsymbol{\hat{\alpha}^T} = [\boldsymbol{\alpha^T} \quad Q_{sw}]$. The profit of NGF f at the study hour, (6), can be rewritten as follows:

$$\begin{aligned}\pi_f =& (\hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\mu}})^T \hat{\boldsymbol{Q}}_{\boldsymbol{f}} (\hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\mu}}) + (\hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\mu}})^T \hat{\boldsymbol{R}}_{\boldsymbol{f}} + ((\hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\mu}})^T \hat{\boldsymbol{R}}'_{\boldsymbol{f}} \\ & + s'_f) Q_{D0} + s''_f Q_{D0}^2 \end{aligned} \tag{34}$$

where:

$$\hat{\boldsymbol{Q}}_{\boldsymbol{f}} = \begin{pmatrix} \boldsymbol{Q_f} & \vdots & \boldsymbol{Q_{f_a}} \\ \cdots & \cdots & \cdots \\ \boldsymbol{Q_{f_b}} & \vdots & Q_{f_c} \end{pmatrix}, \quad Q_{f_{b_i}} = -\frac{1}{2} b_f v_f u_{f_i} \tag{35}$$

$$Q_{f_{a_i}} \begin{cases} -\frac{1}{2} b_f v_f u_{f_i} & i \neq f \\ -\frac{1}{2} b_f v_f u_{f_i} - v_f & i = f \end{cases}, \quad Q_{f_c} = \frac{1}{2} b_f v_f^2 \tag{36}$$

$$\hat{\boldsymbol{R}}_{\boldsymbol{f}} = \begin{pmatrix} \boldsymbol{R_f} \\ -a_f v_f \end{pmatrix}, \qquad \hat{\boldsymbol{R}}'_f = \begin{pmatrix} \boldsymbol{R'_f} \\ -b_f v_f^2 \end{pmatrix} \tag{37}$$

The elements of $n_g \times n_g$ matrix $\boldsymbol{Q_f}$, $n_g \times 1$ vectors $\boldsymbol{R_f}$, $\boldsymbol{R'_f}$, $\boldsymbol{u_f}$ and scalars S'_f, S''_f, Q_{D0} and v_f are computed using (26)–(30) assuming n_g NGFs are competing in the market. The expected profit of the WPP over different scenarios can be formulated as below:

$$\bar{\pi} = \sum_{k \in K} p_k (\lambda Q_{sw} - blnccost_k) \tag{38}$$

where $blnccost_k$ is balancing cost at scenario k and defined in (10). Equation (38) can be rewritten as below:

$$\bar{\pi} = \sum_{k \in K} p_k (\lambda Q_{sw} - a_{w_k} Q_{sw}) + C \tag{39}$$

$$a_{w_k} = f_{up} u(Q_{w_k} - Q_{sw}) + f_{down} u(Q_{sw} - Q_{w_k}) \tag{40}$$

$$C = \sum_{k \in K} p_k (f_{up} u(Q_{w_k} - Q_{sw}) + f_{down} u(Q_{sw} - Q_{w_k})) Q_{w_k} \tag{41}$$

where u is a step function. Considering the fact that the derivative of C with respect to Q_{sw} is zero for all values of $Q_{sw} \neq Q_{w_k}$, the effect of C is ignored in optimization. From (39)–(41) it is concluded that the WPP can be modeled as a NGF which has a linear marginal cost with a zero slope, $b_w = 0$, and a variable intercept in different scenarios, a_{w_k}, as given in (40). Hence, assuming b_w is a very small positive real number, (39) can be written as (34). Written (39) as (34) yields:

$$\begin{aligned}\bar{\pi}_w =& (\hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\mu}})^T \hat{\boldsymbol{Q}}_{\boldsymbol{w}} (\hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\mu}}) + (\hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\mu}})^T \hat{\boldsymbol{R}}_w \\ & + ((\hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\mu}})^T \hat{\boldsymbol{R}}'_w + s'_w) Q_{D0} \end{aligned} \tag{42}$$

where:

$$\hat{\boldsymbol{Q}}_{\boldsymbol{w}} = \begin{pmatrix} & & & \boldsymbol{z_1} & & & \\ b_g u_{g_1} & \cdots & b_g u_{g_g} + 1 & \cdots & b_g u_{g_{n_g}} & \vdots & -b_g v_g \end{pmatrix} \tag{43}$$

$$\hat{\boldsymbol{R}}_{\boldsymbol{w}} = \begin{pmatrix} \boldsymbol{z_2} \\ -\sum_{k \in K} p_k a_{w_k} \end{pmatrix}, \quad \hat{\boldsymbol{R}}'_{\boldsymbol{w}} = \begin{pmatrix} \boldsymbol{z_2} \\ b_g v_g \end{pmatrix}, \quad s'_w = \frac{C}{Q_{D0}} \tag{44}$$

b_g is the slope of the bid function of an arbitrary unbound NGF at the market equilibrium and u_{g_i} and v_g are computed using (24). $\boldsymbol{z_1}$ is a $n_g \times (n_g + 1)$ zero matrix and $\boldsymbol{z_2}$ is a $n_g \times 1$ zero vector. Comparing (34) and (42) with (6), yields that SFE can be modeled as (7)–(9) in the GP scheme.

C. Appendix C: SFE Model for the SF Scheme

In SF scheme, the WPP bids an affine supply function to the ISO. Comparing (39) and (4) concludes that the WPP can be modeled as a NGF which has a linear marginal cost with a zero slope, $b_w = 0$, and a variable intercept in different scenarios, a_{w_k}, as given in (40). Hence, assuming b_w is a very small positive real number, the WPP^{\prime}s profit at scenario k can be written as (6). The only parameter of (6) that depends on a_{w_k} is $\boldsymbol{R_w}$ (see (28) in Appendix A), which is shown with $\boldsymbol{R_{w_k}}$. The expected profit of the WPP also can be written as (6) assuming $\boldsymbol{R_w} = \sum_{k \in K} p_k(\boldsymbol{R_{w_k}})$. Therefore, SFE can be modeled as (7)–(9) in the SF scheme.

REFERENCES

[1] T. Dai and W. Qiao, "Optimal bidding strategy of a strategic wind power producer in the short-term market," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 707–719, Jul. 2015.

[2] M. Goloshchapova, "Results of wind dispatch pilot," Alberta Electric System Operator (AESO), Feb. 2013.

[3] S. N. Singh and I. Erlich, "Wind power trading options in competitive electricity market," in *Proc. IEEE Power Eng. Soc. General Meeting*, 2006, pp. 7–13.

[4] T. Dai and W. Qiao, "Trading wind power in a competitive electricity market using stochastic programing and game theory," *IEEE Trans. Sustain. Energy*, vol. 4, no. 3, pp. 805–815, Jul. 2013.

[5] A. Fabbri *et al.*, "Assessment of the cost associated with wind generation prediction errors in a liberalized electricity market," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1440–1446, Aug. 2005.

[6] J. Liang, S. Grijalva, and R. G. Harley, "Increased wind revenue and system security by trading wind power in energy and regulation reserve markets," *IEEE Trans. Sustain. Energy*, vol. 2, no. 3, pp. 340–347, Jul. 2011.

[7] M. Zugno, J. M. Morales, P. Pinson, and H. Madsen, "Pool strategy of a price-maker wind power producer," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3440–3450, Aug. 2013.

[8] Y. Liu, C. Jiang, J. Shen, and J. Hu, "Coordination of hydro units with wind power generation using interval optimization," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 443–453, Apr. 2015.

[9] B. Zhang, R. Johari, and R. Rajagopal, "Competition and coalition formation of renewable power producers," *IEEE Trans. Power Syst.*, vol. 30, no. 3, pp. 1624–1632, May 2015.

[10] S. Delikaraoglou, A. Papakonstantinou, C. Ordoudis, and P. Pinson, "Price-maker wind power producer participating in a joint day-ahead and real-time market," in *Proc. 2015 Int. Conf. Eur. Energy Market (EEM)*, May 2015, pp. 1–5.

[11] M. Bueno, M. A. Moreno, J. Usaola, and F. J. Nogales, "Strategic wind energy bidding in adjustment markets," in *Proc. 2010 Int. Universities Power Engineering Conf. (UPEC)*, Aug. 2010, pp. 1–6.

[12] L. Baringo and A. J. Conejo, "Strategic offering for a wind power producer," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4645–4654, Nov. 2013.

[13] L. Baringo and A. J. Conejo, "Offering strategy of wind-power producer: A multi-stage risk-constrained approach," *IEEE Trans. Power Syst.*, to be published.

[14] M. Banaei and M. Oloomi Buygi, "How wind power plants can affect electricity markets by gaming on their generation power?," in *Proc. 2013 Iranian Conf. Electrical Engineering (ICEE)*, May 2013, pp. 1–6.

[15] M. Banaei and M. Oloomi Buygi, "Impacts of strategic behavior of wind power plants on electricity markets: A supply function equilibrium approach," in *Proc. 2013 Iranian Conf. Electrical Engineering (ICEE)*, May 2013, pp. 1–6.

[16] B. Willems, I. Rumiantseva, and H. Weigt, "Cournot versus supply functions: What does the data tell us?," *Energy Econ.*, vol. 31, pp. 38–47, 2009.

[17] B. F. Hobbs, C. B. Metzler, and J. S. Pang, "Strategic gaming analysis for electric power systems: An MPEC approach," *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 638–645, May 2000.

[18] M. Oloomi Buygi, H. Zareipour, and W. D. Rosehart, "Impacts of large-scale integration of intermittent resources on electricity markets: A supply function equilibrium approach," *IEEE Syst. J.*, vol. 6, no. 2, pp. 220–232, Jun. 2012.

[19] E. Y. Bitar, R. Rajagopal, P. P. Khargonekar, K. Poolla, and P. Varaiya, "Bringing wind energy to market," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1225–1235, Aug. 2012.

[20] P. Pinson, C. Chevallier, and G. N. Kariniotakis, "Trading wind generation from short-term probabilistic forecasts of wind power," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1148–1156, Aug. 2007.

[21] G. P. Swinand and M. Godel, "Estimating the impact of wind generation on balancing costs in the GB electricity markets," in *Proc. 2012 Int. Conf. Eur. Energy Market (EEM)*, May 2012, pp. 1–8.

[22] J. Liang, S. Grijalva, and R. G. Harley, "Increased wind revenue and system security by trading wind power in energy and regulation reserve markets," *IEEE Trans. Sustain. Energy*, vol. 2, no. 3, pp. 340–347, Jul. 2011.

[23] Report on Transparency of Electricity Market Data in the Region of South-East Europe, 2014 [Online]. Available: https://www.entsoe.eu/news-events/announcements/announcements-archive/Pages/News/Transparency-South-East-Europe-energy-market-data.aspx

Mohsen Banaei received his B.Sc. and M.Sc. degrees in Electrical Engineering from the Ferdowsi University of Mashhad, Mashhad, Iran. He is currently working toward the Ph.D. degree in Electrical Engineering in the Ferdowsi University of Mashhad. His research interests include operation and planning of power systems and renewable resources.

Majid Oloomi Buygi (S'03–M'09) received the Ph.D. degree from Darmstadt University of Technology, Darmstadt, Germany. He is currently an Associate Professor with the Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran. His main research interests include power system operation and planning.

Hamidreza Zareipour (S'03–M'08–SM'09) received the Ph.D. degree in electrical engineering from the University of Waterloo, Waterloo, ON, Canada, in 2006. He is currently a Professor with the Department of Electrical and Computer Engineering, University of Calgary, Calgary, AB, Canada. His current research interests include economics, operation, and planning of electric energy systems.