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Strategic gaming of wind power producers joined with thermal units in electricity markets

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Wind power producers are getting ready to participate in electricity markets as well as conventional units. This poses challenges to power system operators. Wind speed forecasting error increases power imbalance at real time operation, and hence, profits of wind power producers decrease due to balancing costs. A recently proposed scheme for reducing wind power plants power imbalance and increasing their profits is to team up each wind power producer with a non-wind generating firm. The joint firm participates in the market by bidding the joint supply function as a single unit. The objectives of this paper are 1) improving the efficiency of this scheme by considering both benefits and losses of positive and negative balancing prices, 2) determining the optimal generation capacity for the joined firm for maximum profitability of the scheme, and 3) performing sensitivity analysis on different parameters to determine the range of profitability of the scheme in different conditions. In order to evaluate the efficiency of the model, behavior of other generating firms should be known. To this end, supply function equilibrium model is used to determine the optimal behavior of generating firms considering their interactions. Performance of the improved scheme is discussed using a test system.

1. Introduction

Wind-powered electricity generation has grown significantly around the world. Costs of wind generation development have decreased significantly. Governments are also moving towards reducing subsidies for wind generators [1]. Payment mechanism of WPPs is changing from feed-in tariff to feed-in premium tariff. The feed-in tariff guarantees a fixed price for producing every MWh wind power generation [2]. Under the feed-in premium tariff WPPs receive market price plus a fixed price, which is less than the fixed price of the feed-in tariff [3,4]. These reasons motivate WPPs to consider strategic participation in competitive markets.

On the other hand, unpredictable nature of the wind power may cause imbalance between the 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 forecast their wind power generation more accurately [5]. Thus, there is a cost for the uncertainty associated with the wind power, which may impact wind generators' strategic behavior.

Several studies on the behavior of WPPs have been reported in the literature. Effects of large scale integration of WPPs on the electricity price in New England power system is studied in Ref. [6]. WPPs are considered as price-takers and grid structure impacts are considered in the proposed model. Reference [7] studies the impacts of participation of WPPs as price-taker market players on locational marginal prices and proposes a new objective function for optimizing the value of the proposed power of the WPPs so as to maximize social welfare. In Ref. [8] a stochastic mixed-integer linear programming approach is proposed to find the optimal bidding strategy of a thermal generating unit joined with a WPP. Uncertainties in electricity market price and power output of the WPP are modeled using discrete scenarios. Impacts of bidding strategy of the thermal unit and the WPP on the strategic bidding of the other market players and consequently market prices are ignored. Reference [9] proposes a Stochastic Cournot Nash Equilibrium model to find the optimal bidding strategy of WPPs in a pool-based electricity market. Conventional generators and consumers are assumed to be non-strategic and they are only considered for the market clearing problem. In Ref. [10], stochastic

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Abbreviations

Firms

NGF	Non-Wind generating Firm
WPP	Wind Power Producer

Schemes

GP scheme	Generation Power 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

programming is used to generate optimal bidding strategies for wind and conventional power producers in both energy and reserve markets. In Ref. [11], it is shown that WPPs can increase their revenues by optimally bidding in both energy and reserve markets. Thus, part of the wind power variations is diverted into the system reserve, reducing the need for additional reserve required to balance short-term variations of wind power. In Ref. [12], WPPs are considered as price-takers in the day-ahead market and as price-makers in the balancing market. In Ref. [13], the strategic offering of a WPP is modeled as a Mathematical Problem with Equilibrium Constraints (MPEC) considering uncertainty in wind generation and balancing market price. The WPP decides about both the offer price and wind power level. Strategic offering of a WPP as an Equilibrium Problem with Equilibrium Constraints (EPEC) is modeled in Refs. [14–16]. In Ref. [14] WPP bids a supply function like other market players. In Ref. [15] WPP optimizes its power bid while other market players bid a supply function to ISO. Reference [16], which is the basis of this paper, proposes a SFE model for an electricity market with strategic conventional power plants and a large scale WPP. In the presented model in Ref. [16], it is proposed that the WPP and joined NGF participate in the electricity market by submitting a bid function as a single unit called the WN firm. The goal of joining is to reduce the WPP's balancing cost, omit uncertainty from electricity market, and reduce the necessary regulating reserves. This firm pays a penalty for negative balancing cost and reduces its output power to avoid from positive power imbalance. Problem is solved from the viewpoint of the ISO which tends to find the scheme that leads to the lowest electricity price for consumers. Simulation results shows that the proposed scheme leads to the lowest electricity price for consumers in comparison with other schemes presented in Ref. [16]. Incomes associated with positive power imbalance, optimal generation capacity of the joined NGF and effect of variation of different parameters on the efficiency of the model are ignored in the proposed model.

Contributions of this paper are as follows: 1) This paper solves the SFE problem from the view point of the ISO which tends to find the scheme that provides more profit for the WPP and joined NGF, 2) This paper considers both positive and negative balancing prices, while reference [16] ignores the income resulted from the positive power balancing, 3) In order to reach the maximum efficiency of the coalition, a formula for determining the optimal capacity of the joined NGF is presented, and 4) Impacts of different parameters such as parameters of wind speed distribution, parameters of cost function of joined NGF, parameters of wind turbine, and balancing prices on the efficiency of the proposed model are investigated.

The remainder of this paper is organized as follows: In Section 2, main assumptions and required background are reviewed. In Section 3, problem is formulated and optimal capacity of the joined NGF is calculated. To determine the impacts of strategic bidding of WPPs, case studies are presented and analyzed in Section 4. Finally, conclusions are presented in Section 5.

2. Assumption and background

2.1. Assumption and problem definition

Consider a day-ahead pool electricity market with strategic NGFs and a large-scale WPP. Transmission constraints are ignored. It is assumed that each generating firm offers a linear supply function to ISO. The ISO determines generation powers and market price by maximizing the social welfare. Here we focus on 1 h of the next day. Suppose that the WPP can participate in the electricity market strategically. There are some operational and technical issues for strategic participation of WPPs in electricity markets. WPPs' power is intermittent and they cannot predict their output power precisely. Moreover, output power of WPPs is not controllable. This leads to inaccurate bids by the WPPs and also power imbalance between scheduled power by the ISO and the actual output power of WPPs. In this paper, as in some European countries [17,18], it is assumed that the WPP is responsible for its power imbalance and pays the imbalance cost. This means if the WPP generates more that its scheduled power, its extra output power is purchased in a price lower that market price and if the WPP generates lower than the scheduled power by the ISO, it should pay a penalty higher than the market price for each MWh undelivered power. Hence, strategic participation of the WPP in the electricity market can decrease its profit considerably due to high balancing cost.

In this paper, it is proposed that 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 and this scheme is referred to as WN scheme. Joining the WPP and NGF helps the WPP to reduce its power imbalance using the free generation capacity of the joined NGF, reduces the balancing cost, and consequently increases the profit of the WN firm. It also reduces the necessary regulating reserves.

The proposed scheme is compared with another strategic scheme which is introduced in Ref. [15]. This scheme is referred to as GP scheme. Reference [14] could also be considered for the comparison but different simulation result shows that the profit of the WPP in Ref. [15] is usually greater than its profit in Ref. [14]. It's also assumed that the renewable supporting tariffs are similar for both WN and GP schemes. In order to study the impacts of strategic bidding of the WPP, we need 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 to its Nash equilibrium.

SFE model is used to determine the strategic bidding of generating firms at market Nash equilibrium. Wind power uncertainty is modeled with some scenarios. The WPP determines its bid by maximizing its expected profit over the wind power scenarios. Since uncertainty in wind power generation is covered by the ISO using balancing units, power producers except the WPP do not observe wind uncertainty. Hence, other firms determine their bids by maximizing their profit in a deterministic environment. Deterministic SFE model is reviewed in the next subsection.

2.2. Deterministic SFE model

Consider a uniform electricity market. 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, $\rho(Q_{sf}) = \alpha_f + b_f Q_{sf}$, 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. ISO's social welfare optimization problem is as below [19]:

$$Max \quad J_{ISO} = \sum_{j \in D}\left(c_j Q_{Dj} - \frac{1}{2} d_j Q_{Dj}^2\right) - \sum_{f \in F}\left(\alpha_f Q_{sf} + \frac{1}{2} b_f Q_{sf}^2\right) \tag{1}$$

$$s.t. \quad \sum_{f \in F} Q_{sf} - \sum_{j \in D} Q_{Dj} = 0 \tag{2}$$

$$Q_{sf}^{\min} \le Q_{sf} \le Q_{sf}^{\max} \tag{3}$$

where, $Q_{sf}^{\min}$ and $Q_{sf}^{\max}$ are capacity limits of the firm f, F is the set of generation 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 [19]:

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

$$s.t. \quad \textit{Optimization problem } (1) - (3) \tag{5}$$

where, λ is the MCP. SFE problem can be formulated by a set of coupled bi-level optimizations (4)–(5) for every f in F [19]. 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 Karush-Kuhn-Tucker (KKT) optimality conditions, and then solving the KKT optimality conditions of the outer-level optimization problems together, i.e., (4) subject to the KKT conditions of (5) for all firms. KKT conditions of the ISO optimization lead to:

$$\lambda = \alpha_f + \mu_f + b_f Q_{sf} = c_j - d_j Q_{Dj} \quad \forall f \in F \tag{6}$$

where $\mu_f = \mu_f^{\max} - \mu_f^{\min}$, and $\mu_f^{\max}$ and $\mu_f^{\min}$ are dual variables of upper and lower generation limits respectively. Rearranging (6) yields:

$$Q_{sf} = v_f + u_f^T(\alpha + \mu) \tag{7}$$

where:

$$u_{f_j} = \frac{1}{b_f b_j B}, \quad u_{f_f} = \frac{-b_f B - 1}{b_f^2 B}, \quad v_f = \frac{1}{b_f B} \tag{8}$$

$$B = \begin{cases} \sum_{i \in F} 1/b_i & \text{elastic load} \\ \sum_{i \in F} 1/b_i + \sum_{j \in D} 1/d_j & \text{inelastic load} \end{cases} \tag{9}$$

Assuming n_g is the number of all NGFs, α is a $n_g \times 1$ vector which consists of the bids of all NGFs, $\mu = \mu^{max}$-μ^{min}, and μ^{max} and μ^{min} are $n_g \times 1$ vectors which consist of the dual variables of upper and lower generation limits, respectively. By substituting (6) and (7) in (4), the profit of firm f can be written as a quadratic function of α with negative second derivative, as follows [19]:

$$\pi_f = (\alpha+\mu)^T Q_f (\alpha+\mu) + (\alpha+\mu)^T R_f + \left((\alpha+\mu)^T R'_f + s'_f\right) Q_{D0} + s''_f Q_{D0}^2 \tag{10}$$

The elements of $n_g \times n_g$ matrix Q_f, $n_g \times 1$ vectors R_f and R'_f, and scalars s'_f, s''_f and Q_{D0} are defined as follows [19]:

$$Q_{f_{ij}} = \frac{B_f + B_{Q_{ij}}}{2 b_i b_j B^2}, \quad B_f = \frac{1}{b_f}, \quad C_f = \frac{a_f}{b_f} \tag{11}$$

$$B_{Q_{ij}} = \begin{cases} 0 & i \ne f \quad j \ne f \\ B^2 b_j & i = f \quad j = f \\ -B & i = f \quad j \ne f \\ B & i \ne f \quad j = f \end{cases} \quad \forall i, j \in F \tag{12}$$

$$R_{f_i} = \begin{cases} -v_i\left(C_f - a_i B\right) & i = f \\ -v_i C_f & i \ne f \end{cases} \quad \forall i \in F \tag{13}$$

$$R'_{f_i} = \frac{B_f}{b_i B^2} \quad \forall i \in F, \quad S'_f = \frac{-C_f}{B}, \quad s''_f = \frac{B_f}{2B^2} \tag{14}$$

$$Q_{D0} = \begin{cases} \sum_{j \in D} c_j/d_j & \text{elastic load} \\ \text{total demand} & \text{inelastic load} \end{cases} \tag{15}$$

SFE model can be simplified as follows [19]:

$$H(\alpha+\mu) + R + R' Q_{D0} - U\mu \tag{16}$$

$$V Q_{D0} + U(\alpha+\mu) \le Q_s^{\max} \quad \perp \quad \mu^{\max} \tag{17}$$

$$V Q_{D0} + U(\alpha+\mu) \ge Q_s^{\min} \quad \perp \quad \mu^{\min} \tag{18}$$

where,

$$\alpha = \begin{bmatrix} \alpha_1 \\ \alpha_1 \\ \vdots \\ \alpha_1 \end{bmatrix}, \quad R = \begin{bmatrix} R_{1_1} \\ R_{2_2} \\ \vdots \\ R_{n_g n_g} \end{bmatrix} \quad R' = \begin{bmatrix} R'_{1_1} \\ R'_{2_2} \\ \vdots \\ R'_{n_g n_g} \end{bmatrix} \tag{19}$$

$$H = \begin{bmatrix} 2Q_{1_{11}} & Q^f_{1_{12}} & \cdots & Q^f_{1_{1,n_g}} \\ Q^f_{2_{22}} & 2Q_{2_{22}} & \cdots & Q^f_{2_{2,n_g}} \\ \vdots & \vdots & \ddots & \vdots \\ Q^f_{n_g n_{g,1}} & Q^f_{n_g n_{g,2}} & \cdots & 2Q_{n_{g n_g, n_g}} \end{bmatrix} \tag{20}$$

By solving (16)–(18), SFE, i.e., $\alpha_f^* \forall f \in F$, is computed. In Ref. [19], 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 SFE. A bound firm at SFE is a firm that one of its generation limits is active in SFE. Hence, bound firms at SFE must be identified and eliminated from SFE model, i.e. (16)–(18). An algorithm for computing probabilistic SFE is presented in Ref. [19]. The algorithm can be easily used for computing deterministic SFE assuming there is only one scenario for uncertainty. At each stage of this algorithm, (16)–(18) are solved. The largest dual variable associated with generation limits is identified and the related firm is omitted. Omitting a firm means fixing the output power of it at its active limit and subtracting power of its active generation limit from the load. This process continues until all bound firms are identified, omitted, and SFE is computed.

3. Problem formulation

3.1. Modeling of WN scheme

Output power of the WPP is a random variable with a probability distribution. So, its possible future scenarios and the associated probabilities are generally known. Output power of the WPP can be quantized into a set of discrete scenarios, say, $Q_{w_1}, Q_{w_2}, \dots, Q_{w_k}, \dots, Q_{wn_k}$ with probabilities of $\rho_{w_1}, \rho_{w_2}, \dots, \rho_{w_k}, \dots, \rho_{w_{n_k}}$. k is the index of scenarios, n_k is the number of scenarios, and K is the set of all future scenarios of output power of the WPP. In real time, the wind power generation is different with the considered value in the ISO's day-ahead scheduling. It is assumed that the ISO covers the imbalance using balancing utilities. The WPP is charged for balancing cost. It's assumed that if the output power of the WPP is greater than its scheduled power in the day-ahead market (positive imbalance), it receives f_{up} for each MWh extra power generation (positive balancing revenue). f_{up} is called positive balancing price and is less than the MCP. If the output power of the WPP is less than its scheduled power (negative imbalance), it pays f_{down} for each MWh lack of power generation (negative balancing cost). f_{down} is called negative balancing price and is greater than the MCP. Sum of positive balancing revenue and negative balancing cost under all wind generating scenarios is called balancing cost. This can be considered as a penalty mechanism for the WPP to force it to improve its wind power estimations. In the following subsections, the WN scheme is formulated, optimal generating capacity of joined NGF is determined, and the GP scheme is introduced.

In the proposed scheme, the WPP teams up with a NGF and the aggregated firm (WN) participates in the electricity market as a single firm. The WN firm submits a linear supply function to the ISO. The slope of its supply function is equal to the slope of marginal cost of the joined NGF and its intercept is determined such that the profit of the WN firm is maximized. 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 negative balancing cost, and 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 purchased with positive balancing price. Suppose Q_{swn} is scheduled power of the WN firm in day-ahead market, Q_{n_k} is generation power of the joined NGF at scenario k and $Q_{n_{\max}}$ is its maximum capacity. Now, assume that K_1, K_2, and K_3 are sets of scenarios in which $Q_{swn} \le Q_{w_k}$, $Q_{w_k} \le Q_{swn} \le Q_{n_{\max}} + Q_{w_k}$, $Q_{swn} \ge Q_{n_{\max}} + Q_{w_k}$, respectively. Above-mentioned assumptions conclude that the WPP output is equal to Q_{w_k} at each case and the output power of the NGF varies as below:

$$Q_{n_k} = 0 \quad \forall k \in K_1 \tag{21}$$

$$Q_{n_k} = Q_{swn} - Q_{w_k} \quad \forall k \in K_2 \tag{22}$$

$$Q_{n_k} = Q_{n_{\max}} \quad \forall k \in K_3 \tag{23}$$

Therefore, expected profit of the WN firm is equal to:

$$\overline{\pi}_{wn} = \lambda Q_{swn} - \sum_{k \in K} \rho_k \psi_{wn_k} \tag{24}$$

where

$$\psi_{wn_k} = -f_{up}\left(Q_{w_k} - Q_{swn}\right) \quad \forall k \in K_1 \tag{25}$$

$$\psi_{wn_k} = a_n\left(Q_{swn} - Q_{w_k}\right) + 1/2 b_n \left(Q_{swn} - Q_{w_k}\right)^2 \quad \forall k \in K_2 \tag{26}$$

$$\psi_{wn_k} = a_n Q_{n_{\max}} + \frac{1}{2} b_n Q_{n_{\max}}^2 + f_{down}\left(Q_{swn} - Q_{n_{\max}} - Q_{w_k}\right) \quad \forall k \in K_3 \tag{27}$$

Equation (13) can be rearranged as following:

$$\overline{\pi}_{wn} = \sum_{k \in K} \rho_k \left(\lambda Q_{swn} - a_{wn_k} Q_{swn} - \frac{1}{2} b_{wn_k} Q_{swn}^2 \right) + C \tag{28}$$

Parameters a_{wn_k} and b_{wn_k} and C can be written as bellow:

$$a_{wn_k} = f_{up} \quad b_{wn_k} = 0 \quad \forall k \in K_1 \tag{29}$$

$$a_{wn_k} = a_n - b_n Q_{w_k} \quad b_{wn_k} = b_n \quad \forall k \in K_2 \tag{30}$$

$$a_{wn_k} = f_{down} \quad b_{wn_k} = 0 \quad \forall k \in K_3 \tag{31}$$

$$\begin{aligned} C = \sum_{k \in K} \rho_k \Big(& f_{up} Q_{w_k} u\left(Q_{w_k} - Q_{swn}\right) + \left(a_n Q_{w_k} - \frac{1}{2} b_n Q_{w_k}^2 \right) u\big(Q_{swn} \\ & - Q_{w_k}\big) u\left(Q_{n_{\max}} + Q_{w_k} - Q_{swn}\right) + \Big(f_{down}\left(Q_{n_{\max}} + Q_{w_k}\right) \\ & - \left(a_n Q_{wn_{\max}} + \frac{1}{2} b_n Q_{wn_{\max}}^2 \right) \Big) u\left(Q_{swn} - Q_{n_{\max}} - Q_{w_k}\right) \Big) \end{aligned} \tag{32}$$

where, u is the step function. Considering the fact that the derivative of C with respect to Q_{swn} is zero for all $Q_{swn} \ne Q_{w_k}$ and $Q_{swn} \ne Q_{n_{\max}} + Q_{w_k}$, the effect of C is ignored in the optimization.

Using (28), 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 Q_f, R_f, and R'_f for other units, can be calculated using formulas given in Subsection 2.2 assuming $b_{wn_k} = b_n$. For the WN firm, matrices Q_{wn}, R_{wn} and R'_{wn} are defined for each subset of scenarios, i.e., for K_1, K_2 and K_3 using formulas given in Subsection 2.2 and considering Equations (29)–(31). Let use subscript j to denote these subsets. Hence, matrices Q_{wn_j}, R_{wn_j} and R'_{wn_j} are defined for $j = 1, 2, 3$. Moreover, since a_{wn} and consequently R_{wn_2} have different values in different scenarios k in K_2, subscript k is used for R_{wn_2} and it is shown as $R_{wn_{2_k}}$. Considering above-mentioned definitions, all above statements, Equations (16)–(18) can be rewritten as the following equations [16]:

$$\begin{aligned} & \sum_{k \in K_1} \rho_k \left(H_1(\alpha + \mu) + R_1 + R'_1 Q_{D0} \right) \\ & + \sum_{k \in K_2} \rho_k \left(H_2(\alpha + \mu) + R_{2_k} + R'_2 Q_{D0} \right) \\ & + \sum_{k \in K_3} \rho_k \left(H_3(\alpha + \mu) + R_3 + R'_3 Q_{D0} \right) - U\mu = 0 \end{aligned} \tag{33}$$

$$VD_{D0} + U(\alpha + \mu) \le Q_s^{\max} \quad \perp \quad \mu^{\max} \tag{34}$$

$$VD_{D0} + U(\alpha + \mu) \ge Q_s^{\min} \quad \perp \quad \mu^{\min} \tag{35}$$

SFE is computed by solving (22)–(24) using the proposed algorithm in Section 2.2. By solving the SFE model, market price, optimal strategy of the market players and expected profit of the WN are determined. Comparing formulas (21)–(35) and the proposed formulation in Ref. [16] shows that if $f_{up} = 0$ both formulations are the same.

3.2. Optimal generation capacity for NGF

Generation capacity of the joined NGF plays an important role in the efficiency of the proposed scheme. A low generating capacity NGF can't cover the power imbalance of the WPP that leads to decrease in proposed power and increase in balancing cost, and consequently decrease in the profit of the WN firm. Choosing a high generating capacity NGF can decrease the profit of WN firm, too. This happens when the cost of generating power by NGF becomes greater than the balancing cost. In order to find the optimal generation capacity of joined NGF, i.e., $Q^*_{n_{\max}}$, the first derivative of $\overline{\pi}_{wn}$ with respect to $Q_{n_{\max}}$ is computed. For the sake of simplicity, it's assumed $\partial\lambda/\partial Q_{n_{\max}} = \partial Q_{swn}/\partial Q_{n_{\max}} \approx 0$ which it will be shown that this is a good approximation. Solving the equation $\partial\overline{\pi}_{wn}/\partial Q_{n_{\max}} = 0$ yields:

$$Q^*_{n_{\max}} = (f_{down} - a_n)/b_n \tag{36}$$

where, a_n is intercept and b_n is slope of the marginal cost of the joined NGF. Equation (36) is similar to the revised equation of computing marginal cost of the joined NGF, i.e., $Q_{S_n} = (MC_n - a_n)/b_n$. Comparing these two equations shows that the optimum generating capacity of the joined NGF is where that its marginal cost becomes equal to the negative balancing price. If the joined NGF generates more than this limit, its generation cost gets higher than balancing cost and the profit of WN firm decreases.

3.3. GP scheme

In order to compare the result of the WN scheme with other strategic schemes, case study is applied to the proposed bidding strategy schemes in Ref. [15], too. In Ref. [15] a SFE model for an electricity market with thermal power plants and a strategic large-scale WPP is proposed. Thermal power plants participate in the electricity market by submitting a supply function bid to the ISO. Since the cost function of the WPP is not similar to the other market players' cost functions and its marginal cost is almost equal to zero, the WPP's strategic behavior cannot be modeled similar to other market players or it needs some new assumptions that reduces the accuracy of results. In order to overcome this problem, it is assumed that the ISO allows the WPP to participate in the electricity market by submitting its optimum power considering different output power scenarios and balancing prices. It is also supposed that the ISO accepts all the proposed power by the WPP. This market structure is modeled in Ref. [15] and is known as GP scheme in this paper.

4. Case study

In this section, introduced schemes are applied to a test system. The test system consists of 6 NGFs. Parameters of the marginal cost functions of the NGFs are given in Table 1. It is assumed that the load is inelastic and equal to 20 GW. Suppose a WPP with the capacity of 4 GW is added to the system. 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. Proposed sampling method in Ref. [19] is used to generate wind power generation scenarios.

The mathematical programming software GAMS and the PATH solver was used to solve the EPEC problem. In the following subsections, first simulation results of the WN and GP schemes are presented and compared. then, the accuracy of proposed formula for $Q^*_{n_{\max}}$ is evaluated. Finally, sensitivity analyses are performed on the different parameters of the test system and the results are discussed.

Table 1
Parameters of NGFs [16].

Firms	No.1	No.2	No.3	No.4	No.5	No.6
a ($/MWh)	16	10.8	5.6	26	20	24
b ($/MW²h)	0.007	0.011	0.026	0.005	0.017	0.017
Q_s^{min} *(MW)*	0	0	0	0	0	0
Q_s^{max} *(MW)*	8000	8000	5000	6000	3000	3500

4.1. Simulation results of WN and GP schemes

In the GP scheme, the WPP is a strategic producer which changes its proposed power to maximize its profit. The market equilibrium is computed for this scheme using proposed approach in Ref. [19]. In the WN scheme, the WPP joins NGF 6 and the joined WN firm bids strategically. Simulation results of these schemes are given in Tables 2 and 3 for different balancing prices. for the sake of fair comparison, profit of the joined NGF i.e. NGF 6 is calculated in the GP scheme, too. Generating capacity of the NGF 6 in Table 3 is calculated by Equation (36). Simulation results show that by decreasing positive balancing price, the WN firm increases its generation bid in the day-ahead market to avoid selling the extra generation power with a low price. This causes the MCP and consequently the profit decreases. Comparing columns 2 and 3 of Tables 2 and 3 confirms this issue.

By increasing negative balancing price, the WN withdraws more generation power to avoid paying high balancing cost. This leads to increase in the MCP and the profit. Comparing columns 3 and 4 of Tables 2 and 3 confirms this issue. The GP scheme is applied to another case study in Ref. [15]. Similar results were extracted from that case study. Simulation results also show that the sensitivity of MCP and profit toward the imbalance prices in the WN scheme is lower than their sensitivities in the GP scheme. Comparing Tables 2 and 3 shows that by joining the WPP with a NGF, balancing cost and in fact, necessity to regulating reserves decreases. Minus sign in

Table 2
Market variables at the SFE in GP scheme.

	$f_{up} = 30$, $f_{down} = 70$ ($/MWh)	$f_{up} = 40$, $f_{down} = 70$ ($/MWh)	$f_{up} = 40$, $f_{down} = 80$ ($/MWh)
MCP ($/MWh)	56.47	57.84	58.82
Optimal bid of WPP (GW)	2.53	1.89	1.44
Balancing cost (k$/h)	51.67	10.5	−9.4
Exp. profit of WPP(k$/h)	91.2	99	94.14
Profit of NGF 6 (k$/h)	38.2	30	32.6
Profit of WPP & NGF (k$/h)	121.2	131.6	128.6

Table 3
Market variables at the SFE in WN scheme.

	$f_{up} = 30$, $f_{down} = 70$ ($/MWh)	$f_{up} = 40$, $f_{down} = 70$ ($/MWh)	$f_{up} = 40$, $f_{down} = 80$ ($/MWh)
NGF 6 capacity (GW)	2.7	2.7	3.3
MCP ($/MWh)	58.26	59.12	59.23
Dispatched power (GW)	3.48	3.12	3.09
Exp. balancing cost (k$/h)	8.3	4.2	−11
Exp. profit of WN (k$/h)	134.2	135.9	135.5

third column of Tables 2 and 3 indicates that the revenue of positive power imbalance in this case is more than the cost of negative power imbalance for both schemes. Finally, the profit of the WN firm in the WN scheme is greater than sum of the profits of the WPP and the NGF 6 in the GP scheme. This means that the WN scheme is a better scheme for strategic bidding of the WPP in electricity market from the viewpoint of the WPP and the joined NGF.

4.2. Assessment of accuracy of proposed formula for $Q^*_{n_{\max}}$

$Q^*_{n_{\max}}$ is calculated by Equation (36) ignoring the effect of $\partial\lambda/\partial Q_{n_{\max}}$ and $\partial Q_{swn}/\partial Q_{n_{\max}}$ on the result. This may cause some errors in the result. In order to assess the efficiency of Equation (36), five sets of parameters are considered and applied to the case study. These sets and the calculated $Q^*_{n_{\max}}$ using Equation (36) are presented in Table 4. Simulation results are given in Fig. 1.

Comparing Table 4 and Fig. 1 confirms the efficiency and accuracy of the proposed formula. In fact, calculations show that $\partial\lambda/\partial Q_{n_{\max}}$ and $\partial Q_{swn}/\partial Q_{n_{\max}}$ are less than 0.003 for almost 99.5% of possible values for $Q_{n_{\max}}$ and hence, ignoring their effect on determining the optimal capacity of the joined NGF does not make a considerable difference in the results.

4.3. Sensitivity analyses

In the next subsections, effects of different parameters on the efficiency of the proposed model are discussed.

4.3.1. Effects of the variations of f_{down} and f_{up}

Expected profit of the WN as a function of $Q_{n_{\max}}$ is given in Fig. 2 for different positive balancing prices. f_{down} is assumed 70 \$/MWh.

Table 4
Different sets of parameters.

	Sets				
	1st	2nd	3rd	4th	5th
f_{down} (\$/MWh)	65	75	65	65	60
f_{up} (\$/MWh)	25	25	35	35	50
Capacity of the WPP(GW)	4	4	4	4.5	3.6
shape parameter	1.8	1.8	1.8	1.7	2
scale parameter (m/s)	10	10	10	9	10
Q^*_{max} using Eq. (36) (GW)	2.36	2.93	2.36	2.36	2.07

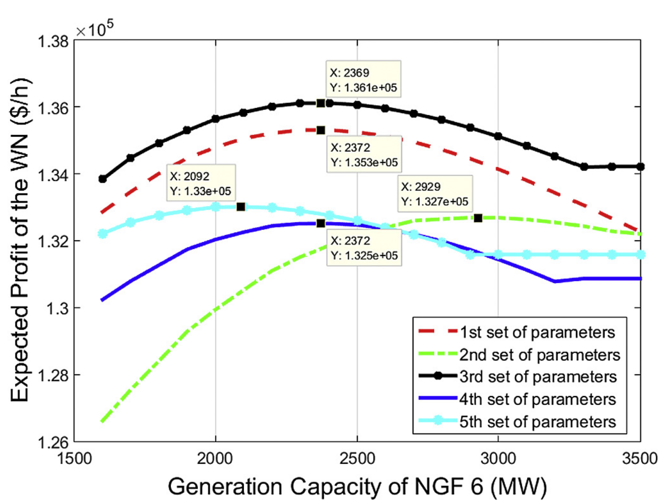

Fig. 1. Expected profit of the WN firm for different sets of parameters.

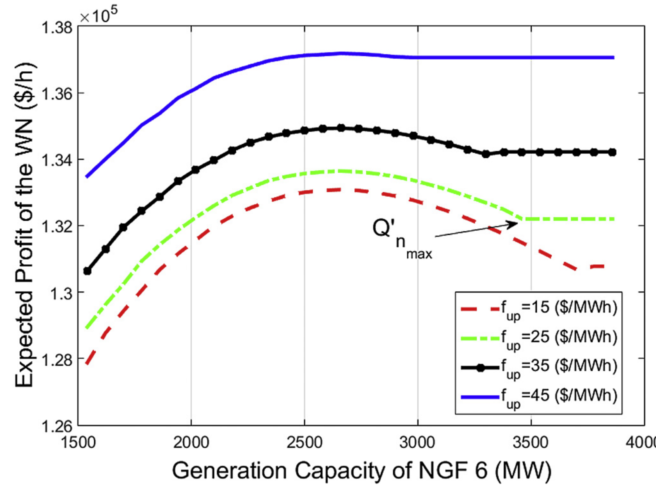

Fig. 2. Expected profit of the WN for different positive balancing price.

As mentioned in Subsection 4.1 and the Fig. 2 confirms, expected profit of the WN increases by increasing the positive balancing price. The profit of the WN gets fixed from a specific generating capacity of NGF 6 i.e., $Q'_{n_{\max}}$. $Q'_{n_{\max}}$ is where the dispatched power of the WN and generating capacity of NGF 6 are equal i.e., $Q_{swn} = Q_{n_{\max}}$. In this capacity, the joined NGF can cover whole negative imbalance of the WPP and negative balancing cost is equal to zero. Considering more capacity for the joined NGF does not make any change in the balancing cost and profit stays fixed. $Q'_{n_{\max}}$ decreases by increasing the f_{up}, because of the decrease in dispatched power.

4.3.2. Effects of variations of wind speed and wind turbine characteristics

Expected profit of the WN as a function of $Q_{n_{\max}}$ is given in Fig. 3 for different negative imbalance prices. f_{up} is assumed 30 \$/MWh. As mentioned in Subsection 4.1 and Fig. 3 confirms, expected profit of the WN decreases by increasing the negative balancing price. Variation of $Q'_{n_{\max}}$ in Fig. 3 is less than its variation in Fig. 2. It means that $Q'_{n_{\max}}$ and Q_{swn} are less sensitive to f_{down} than f_{up}. The expected profit for different negative balancing prices converges to the same point, because for $Q_{n_{\max}} > Q'_{n_{\max}}$ negative balancing cost is zero and the positive balancing cost is equal in all the cases.

Expected profit of the WN and Weibull PDF curves for different shape and scale parameters of wind speed Weibull distribution is presented in Fig. 4. Both scale and shape parameters of the Weibull PDF are 20% increased. Simulation result shows that increase in the both parameters leads to increase in the profit. The sensitivity of the profit toward the shape parameter is greater than the scale parameter. Comparing the Profit and PDF curves indicates that as the distribution gets pushed in towards the right, the Profit of the WN firm increases.

Variations of the expected profit of the WN in the WN scheme and sum of the profits of the WPP and the NGF 6 in the GP scheme versus the variations of shape parameter for two different values of scale parameters are compared in Fig. 5. Simulation result shows that the profit in the WN scheme is greater than the profit in the GP scheme for all different values of scale and shape parameter. Similar simulation is performed for different values of cut-in and rated output speeds of a wind turbine. The result shows that the profit increases by decreasing both cut in and rated output speeds. Profit in the WN scheme is greater than the GP scheme for all kinds of wind turbines.

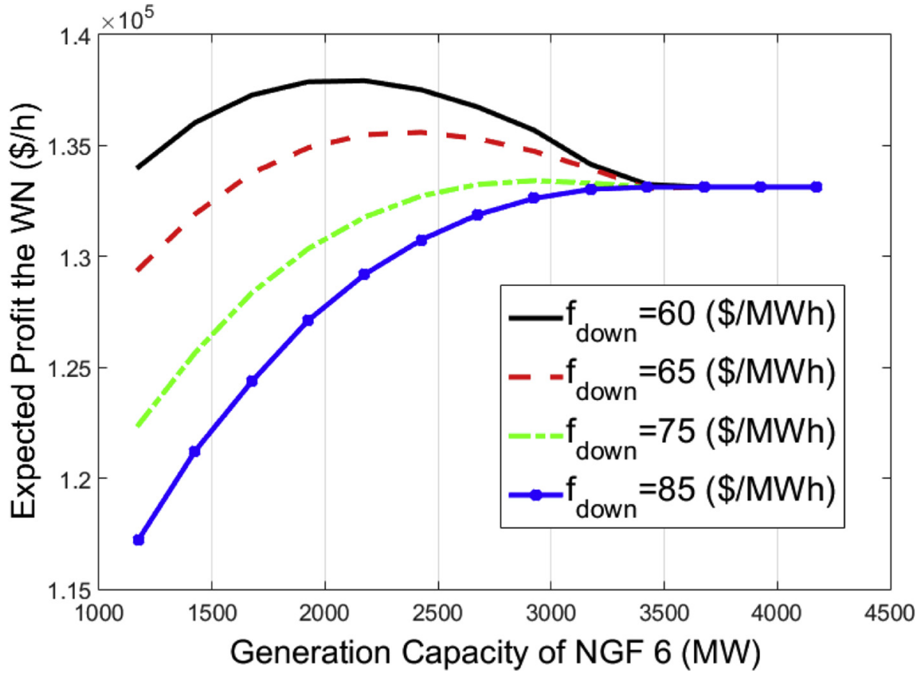

Fig. 3. Expected profit of the WN for different positive balancing price.

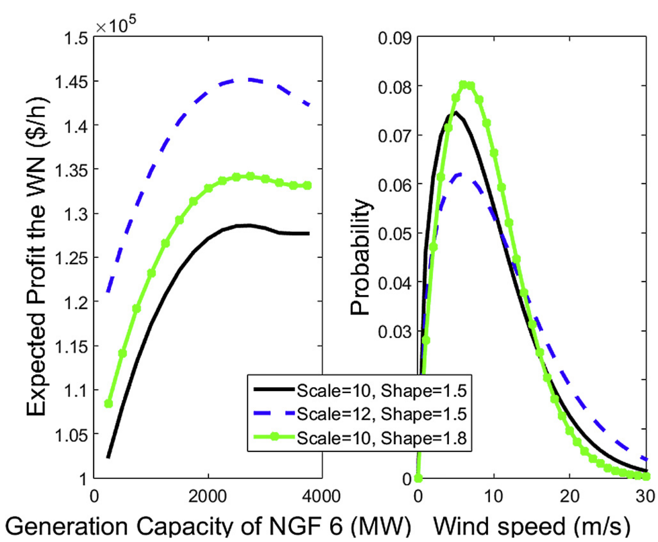

Fig. 4. Fig. 1: Expected Profit of the WN Firm for Different Scale and Shape Parameters. f_{up} = 30 and fdown = 70 \$ = MWh.

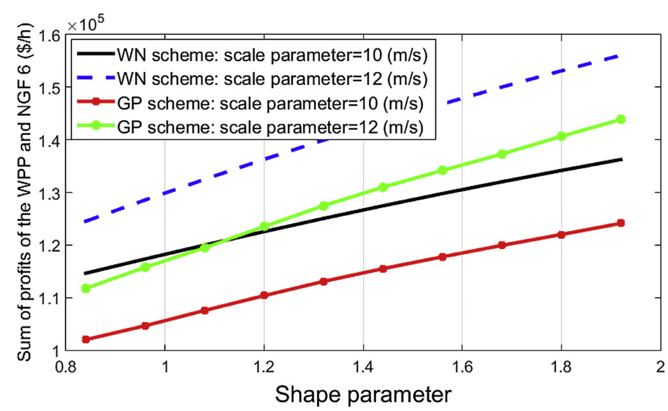

Fig. 5. Comparing the Profit of the WPP and NGF 6 in WN and GP schemes for 2 Different scale parameters. $f_{up} = 30$ and $f_{down} = 70$ \$/MWh.

4.3.3. Effects of variations of cost function of joined NGF

Variations of the expected profit of the WN in the WN scheme and sum of the profits of the WPP and NGF 6 in the GP scheme versus the variation of b_n for two different values of a_n are compared in Fig. 6.

Simulation result shows that, as the coefficients a_n and b_n increases, the profit decreases in both schemes. This happens because by increasing a_n and b_n, NGF 6 becomes a more expensive unit. Hence, its profit from electricity market decreases and cost of covering power imbalance increases. Fig. 6 also shows that the profit in the WN scheme is greater than the profit in the GP scheme only if $b_{n_{\min}} \leq b_n \leq b_{n_{\max}}$. Hence, joining the WPP and the NGFs with very small or very large values for b_n is not recommended. The values of $b_{n_{\min}}$ and $b_{n_{\max}}$ decreases by increasing the value of a_n. $b_{n_{\min}}$

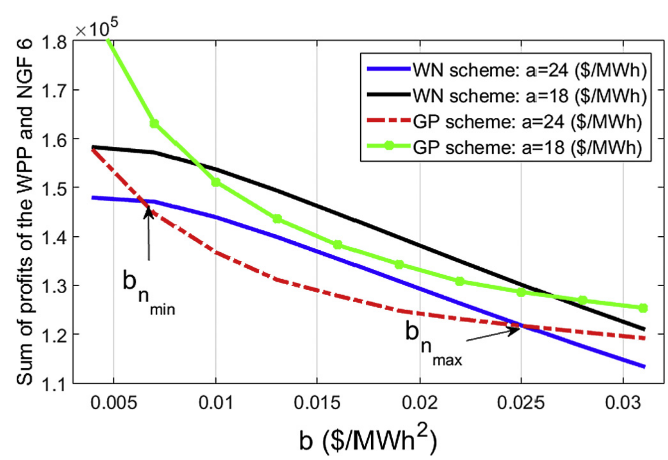

Fig. 6. Expected Profit of the WPP and NGF 6 in WN and GP schemes for 2 values of "a_n". (f_{up} = 20 and f_{down} = 70 \$ = MWh).

and $b_{n_{\max}}$ can be found by try and error for each case study. Similar simulation is performed for the coefficient a_n. The result shows that the expected profit in the WN scheme is greater than the GP scheme for all reasonable range of variations of a_n.

5. Conclusion

The uncertain and unpredictable nature of wind power generation is a major issue for strategic bidding of WPPs in electricity markets. In order to cover the power imbalance of a WPP and reduce its balancing cost, it is proposed to team up the WPP with a NGF and the coalition participates in electricity market as a single firm. Although joining a WPP with a NGF has been studied before in the literature, this paper considers a different viewpoint and proposes new modifications that increase the profitability of the model. First, this paper considers the income that WN can gain due to positive power imbalance, and second, it proposes a formula for optimal capacity of the joined NGF for maximizing the profit of the WN firm and verifies its accuracy. The proposed scheme is compared with GP scheme at market's Nash equilibrium. Simulation results show that joining the WPP with a NGF can increase the profit of the WPP and the joined NGF in comparison to the GP scheme. Impacts of variations in positive and negative balancing prices, wind speed PDF parameters and wind turbine characteristics on the profit of the WN firm are discussed through a sensitivity analysis. Simulation result shows that performance of the WN scheme is better than GP scheme in all above-mentioned sensitivity analyses. Simulation result also shows that in the WN scheme profits of the WPP and the joined NGF are greater than their profits in GP scheme regardless the value of marginal cost intercept of the joined NGF. Moreover, profits of the WPP and the joined NGF in the WN scheme are lower than their profits in GP scheme for very small or very large values for slope of marginal cost of joined NGF. Hence, joining the WPP with the NGFs with such marginal cost functions is not recommended.

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