



Citation for published version:

Sharma, KC, Bhakar, R & Tiwari, HP 2015, 'Stochastic EPEC approach for wind power trading in competitive electricity market' Paper presented at 2014 18th National Power Systems Conference, NPSC 2014, Guwahati, India, 18/12/14 - 20/12/14, . <https://doi.org/10.1109/NPSC.2014.7103830>

DOI:

[10.1109/NPSC.2014.7103830](https://doi.org/10.1109/NPSC.2014.7103830)

Publication date:

2015

Document Version

Peer reviewed version

[Link to publication](#)

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Stochastic EPEC Approach for Wind Power Trading in Competitive Electricity Market

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Abstract—As a consequence of maturing technologies and regulatory interventions, wind power producers (WPPs) are likely to participate strategically in competitive electricity markets. In wind dominated oligopolistic electricity markets, strategic WPPs would optimize their offering bids considering rival behavior. In this perspective, stochastic equilibrium problem with equilibrium constraints (EPEC) model is proposed, to develop optimal offering strategy for WPPs that participate as price-makers in day-ahead electricity market and as price takers in balancing market. Strategic behavior of such WPPs is modeled using bi-level model that can be recast as stochastic mathematical problem with equilibrium constraints (MPEC). In the bi-level model, upper-level represents profit maximization problem of WPPs, while lower-level represents market clearing problem of independent system operator (ISO). Wind power and balancing market price uncertainties are modeled through scenarios. MPECs of all strategic WPPs are solved simultaneously using diagonalisation. Realistic case studies are simulated to show effectiveness of the proposed approach. Obtained results show that proposed approach can increase WPPs' profits significantly.

Index Terms— Electricity Markets, Nash Equilibrium, Mathematical program with equilibrium constraints (MPEC), Equilibrium problem with equilibrium constraints (EPEC), Wind Power.

I. INTRODUCTION

Electrical power industry is being restructured throughout the world to improve system efficiency and offer economic solutions. At same time, uncertainty of fossil fuel prices and environmental concerns are enhancing quantum of renewable power generation. Among the renewable generation, wind power is growing rapidly due to its maturing technology and widespread availability. Wind power integration into power systems causes various operational issues due to its generation variability. Despite these difficulties, penetration of wind power in electricity markets is increasing significantly over the last couple of decades due to regulatory and fiscal interventions from the governments [1].

Over these years, wind power producers (WPPs) are slowly trading towards a dominant position in electricity generation. As they grow in dominance, and with nominal

marginal cost of generation, they are likely to sustain in the market without any regulatory support. They would be interested to participate in evolving pool based electricity markets, similar to conventional generators. Evolving electricity markets are primarily designed for conventional generators, working in day-ahead and balancing market framework. In day-ahead electricity markets, participants must submit bids several hours before actual power delivery. Real-time balance between generation and demand is managed by balancing market, and cleared few minutes before actual operation. Deviation from the committed generation attracts imbalance penalties to the participant from ISO. Due to randomness of wind power availability, actual power delivered by WPPs can differ significantly from their committed generation, leading to high imbalance penalties in pool based electricity markets.

Due to high imbalance penalties and generation uncertainty, trading wind power in pool based electricity markets is a challenging decision-making problem and researchers have attempted to tackle this by a variety of approaches. Markov probability and stochastic programming approach have been used to determine the optimal contracted energy level of WPPs considering wind and imbalance price uncertainties [2], [3]. Probabilistic forecasting has been employed to help WPPs formulate optimal offers with minimum imbalance cost [4]. Multistage stochastic programming approach suggests various trading floors to derive the best offering strategy for a wind power producer [5]. A stochastic model has been proposed to formulate optimal bids of WPPs in LMP based day-ahead electricity markets considering risk of their profit variability [6]. Considering rival behavior, WPPs can trade their energy optimally in day-ahead and balancing electricity market through combined stochastic programming and game theory approach [7]. In the above discussed studies, WPPs are considered as price-takers, and focus on imbalance cost minimization to maximize their profits.

Growing penetration of wind power in electricity markets is likely to offer opportunities for WPPs to behave as price-makers. Therefore, to maximize the profits, they would focus

The first author acknowledges financial support by UGC Grant No. 39-894/2010 (SR).

on offering strategies to affect market-clearing prices. With a price-maker's perspective, WPPs can develop optimal offering strategy in both day-ahead and balancing markets using MPEC approach [8], [9]. MPEC approach has been applied for modeling individual behavior of strategic power producer in electricity markets, but this approach is unable to model strategic behavior of multiple power producers. However, consideration of multiple strategic power producers is significant, as the electricity markets are practically oligopolistic in nature. Modeling for multiple strategic power producers to understand the impact of rival behavior on their strategy, is yet to be visualized in the MPEC approach. Interaction between multiple strategic power producers is generally modeled using game theoretical or equilibrium model as EPEC. Bertrand model based duopoly competition between strategic conventional power producers consisting WPP as a part of their portfolio has been discussed in [10]. Cournot based oligopolistic competition between independent strategic WPPs has been discussed in [11].

This paper develops offering strategy of WPPs that participate as price-maker in day-ahead electricity markets, and as price-taker in balancing market. Strategic behavior of each WPP is modeled using bi-level model. In a bi-level model, upper-level represents profit maximization problem of strategic WPPs, while lower-level represents ISO market clearing problem. Uncertainties involved in wind power and balancing market price are modeled through scenarios. Bilevel model can be recast as MPEC by transposing market-clearing problem into its optimal conditions using Karush-Kuhn-Tucker (KKT) approach. Since MPECs of all WPPs is simultaneously solved using diagonalization method, proposed model is equivalent to EPEC. Proposed model have following advantages: 1) WPPs independently compete in electricity markets rather than being a part of conventional power producer's portfolio. 2) Both price and quantity are decision variables, closely reflecting realistic electricity markets.

II. PROBLEM DESCRIPTION

A. Market Structure

Strategic WPPs can participate in pool based network constrained day-ahead electricity market by submitting their offers in advance. Real-time balance between supply and demand is maintained by balancing market. WPPs can sell/buy their excess/deficit generation in balancing markets. After receiving offers from all participants, ISO clears the market to provide locational marginal price (LMP) at each bus and scheduled generation of each participants. LMP at each bus is obtained as dual variable associated with power balance constraint for this bus in market clearing problem. WPPs can earn their revenue according to LMP of the particular bus where they are located. Balancing market price is uniform at all buses. This framework is commonly practiced in several electricity markets.

B. Uncertainty Characterization

Uncertainty associated with wind power generation and balancing market prices are represented through scenarios. Scenarios are possible outcomes of random input, with corresponding occurrence probability. For scenario generation, time series based autoregressive integrated moving average (ARIMA) model is used. Generated wind speed scenarios are converted into power scenarios, using power curve of corresponding wind turbines installed by WPPs. For accurate representation of any stochastic process, a large number of scenarios are required. Due to computational complexity and time limitations, generated scenarios need to be reduced. The present work does not aim to propose any model to generate accurate scenarios, and uses algorithm from [10] to reduce wind power and balancing market price scenarios. The reduced scenarios reflect the generated power of WPPs and balancing market prices.

III. MATHEMATICAL FORMULATION

This section provides mathematical formulation of proposed stochastic EPEC model, along with its solution procedure.

A. Wind Power Producers Problem

Energy-trading problem of strategic WPPs can be formulated mathematically as follows:

$$\min f_i = \sum_{\omega \in \Omega^\omega} \text{prob}_\omega \left[\sum_{i \in \Omega^w} -\lambda_n^{dm} P_{S_i} + \sum_{i \in \Omega^w} \lambda_\omega^{bm} P_{b_{i,\omega}} \right] \quad (1)$$

$$\text{subject to} \\ P_{b_{i,\omega}} = P_{S_i} - P_{i,\omega} \quad \forall i, \forall \omega \quad (2)$$

$$P_{of_i} + P_{b_{i,\omega}} \leq P_i^{\max}, \quad \forall i, \forall \omega \quad (3)$$

$$P_{of_i} \geq 0, \quad \forall i \quad (4)$$

$$O_i \geq 0, \quad \forall i \quad (5)$$

Where, $P_{i,\omega}$ and λ_ω^{bm} are generated wind power and balancing market in scenario ω with occurrence probability prob_ω . Objective function (1) represents profit of i^{th} strategic WPP, considering balancing cost/income under the assumption that wind power generation cost is zero; therefore, expected payoff is equal to expected profit. Optimization problem (1) of each WPP includes set of variables $x_i = \{P_{of_i}, O_i\}$. WPP revenue is calculated by multiplication of corresponding LMP λ_n^{dm} , where they are located in the system and their scheduled generation being provided by the ISO. Equality constraint (2) states that excess/deficit power $P_{b_{i,\omega}}$ to be sold/ purchased by WPPs must be equal to the difference between their cleared generation P_{S_i} and wind power in each scenario. Constraint (3) states that sum of offered power and excess/deficit power must be less than or equal to installed capacity of WPP P_i^{\max} . Inequality constraint (4) and (5) states that offered power P_{of_i} and price O_i must be greater than or equal to zero.

B. Independent System Operator Problem

After receiving bids from market participants, ISO with an aim to social welfare maximization, can solve market-clearing problem to schedule market operation. The market-clearing problem is convex and non-linear, due to product of WPPs' offered price and cleared generation. The social welfare maximization problem can be formulated mathematically as follows:

$$\begin{aligned} \min f_{iso} = & \sum_{g \in \Omega^g} \lambda_g P_g + \sum_{i \in \Omega^w} O_i P S_i \\ & - \sum_{d \in \Omega^d} \sum_{l \in \Upsilon^d} \lambda_{d,l} P_{d,l} \end{aligned} \quad (6)$$

subject to

$$\begin{aligned} & \sum_{g \in \Psi^g} P_g + \sum_{i \in \Psi^w} P S_i + \sum_{r \in \Omega^{n/r}} f_{n-r} \\ = & \sum_{d \in \Psi^d} \sum_{l \in \Upsilon^d} P_{d,l} : \lambda_n^{dm}, \forall n \end{aligned} \quad (7)$$

$$f_{n-r} = B_{n-r} (\delta_n - \delta_r) : \lambda_{n-r}, \forall n-r, n \neq r \quad (8)$$

$$-f_{n-r}^{\max} \leq f_{n-r} \leq f_{n-r}^{\min} : \mu_{n-r}^{\min}, \mu_{n-r}^{\max}, \forall n-r, n \neq r \quad (9)$$

$$0 \leq P_g \leq P_g^{\max} : \mu_g^{\max}, \mu_g^{\min}, \forall g \quad (10)$$

$$0 \leq P S_i \leq P o f_i : \mu_i^{\min}, \mu_i^{\max}, \forall i \quad (11)$$

$$0 \leq P_{d,l} \leq D F * P_{d,l}^{\max} : \mu_{d,l}^{\min}, \mu_{d,l}^{\max}, \forall d, \forall l \quad (12)$$

$$-\pi \leq \delta_n \leq \pi : \mu_n^{\min}, \mu_n^{\max}, \forall n \quad (13)$$

$$\delta_1 = 0 : \lambda_1 \quad (14)$$

Where, $\lambda_g, \lambda_{d,l}$ and $D F$ are generators' marginal cost, consumers' utility cost and demand factor, respectively. Objective function (6) represents social welfare maximization problem comprising surplus of strategic WPPs, conventional generators and consumers. The optimization problem of ISO consists of a set of primal variables $y = \{P_g, P S_i, P_{d,l}, f_{n-r}, \delta_n\}$. The set of dual variables

corresponding inequality constraints $\mu = \{\mu_{n-r}^{\min}, \mu_{n-r}^{\max},$

$\mu_{d,l}^{\min}, \mu_{d,l}^{\max}, \mu_g^{\max}, \mu_g^{\min}, \mu_n^{\min}, \mu_n^{\max}\}$ and equality

constraints $\lambda = \{\lambda_n^{dm}, \lambda_{n-r}, \lambda_1\}$. Dual variables corresponding

to equality and inequality constraints are assigned to formulate MPEC, as discussed in next subsection. Equality constraint (7) ensures that sum of scheduled power of either wind $P S_i$ or conventional generators P_g , or both, at any particular bus must be equal to meet the demand and injected power at that bus. Constraint (8) states that power flow f_{n-r} in a particular transmission line $n-r$ is equal to the product of corresponding susceptance B_{n-r} and difference between voltage angle at sending δ_n and receiving δ_r bus of line. Inequality constraint (9) enforces the MW flow limit on transmission lines. Constraints (10), (11) and (12) impose

upper and lower bounds on scheduled output of wind, conventional generators and demand. Upper bound is equal to offered bids while lower bound is assumed to be zero. Constraint (13) represents that voltage angle at network bus is within predefined limits. Constraint (14) represents that voltage angle at reference bus should be equal to zero.

A. NLP based Stochastic MPEC Formulation

The above discussed, strategic WPPs' profit maximization and ISO' market clearing problem can be written as a generalized bi-level problem.

$$\min -f_i(x_i, y, \lambda, \omega) \quad (15)$$

subject to

$$g_i(x_i, y, \omega) = 0, \forall \omega \quad (16)$$

$$h_i(x_i) \geq 0 \quad (17)$$

$$\text{where, } y, \lambda \in \left\{ \begin{array}{l} \text{argmin } f_{iso}(y, x) \\ \text{subject to} \\ g_{iso}(y, x) = 0 : \lambda \\ h_{iso}(y, x) \geq 0 : \mu \end{array} \right\} \quad (18)$$

Objective function (15) is defined in terms of WPPs' decision variables and variables of lower-level problem. Eqs. (16) and (17) represent generalized form of equality and inequality constraints of strategic WPP' profit maximization problem. Similarly, Eq. (18) represents generalized form of market clearing problem. During optimization of lower-level problem, variables of upper-level problem x_i can act as parameters. Bi-level problem can be converted into single-level problem, by transposing market-clearing problem into its optimal conditions using Karush-Kuhn-Tucker (KKT) approach [13]. Converted single-level problem is equivalent to MPEC. MPEC can be represented mathematically as:

$$\nabla_y f_{iso}(y, x) - \lambda \nabla_y g_{iso}(y, x) - \mu \nabla_y h_{iso}(y, x) = 0 \quad (19)$$

$$g_{iso}(y, x) = 0 \quad (20)$$

$$0 \leq \mu \perp h_{iso}(y, x) \geq 0 \quad (21)$$

Eq. (19) represents necessary condition of lower-level problem, obtained by its partial differentiation with respect to primal variables. Complementarity constraint (21) states that inequality constraints and corresponding dual variables are orthogonal to each other. These constraints can be handled easily by introducing slack variables.

$$h_{iso}(y, x) - s = 0 \quad (22)$$

$$s \geq 0 \quad (23)$$

$$\mu \geq 0 \quad (24)$$

$$-\mu \circ s \quad (25)$$

Constraint (25) defines Hadamard product of dual and slack variable. Finally, MPEC for each strategic WPP can be formulated as:

$$\min (15) \quad (26)$$

subject to

$$(16), (17), (19), (20), (22) - (25)$$

B. Stochastic EPEC Formulation

Each strategic WPP has its own MPEC, as described in the previous section. MPEC (26) of each strategic WPP is solved simultaneously, and can be represented by EPEC as:

$$MPEC_i \quad \forall i \in \Omega^w \quad (27)$$

Traditional diagonalization is adopted to solve EPEC (27). The proposed simulation procedure is described in the next section.

C. Simulation Procedure

This section details the simulation procedure used to solve the proposed model.

Step 1: Uncertainty characterization: Initialize the strategic WPPs' generated power and balancing market prices through scenarios. For scenario generation and reduction, algorithm from [12] is used.

Step 2: Iteration counter and convergence tolerance initialization: Initialize iteration counter K and convergence tolerance ε to solve MPECs. Iteration counter starts with $k = 1$ and convergence tolerance is defined as $\varepsilon \geq 0$.

Step 3: Starting point initialization: Initialize starting strategy vector $x^{(0)} = (x_1^{(0)}, x_2^{(0)}, \dots, x_i^{(0)})$ of each strategic WPP at iteration counter $k = 0$.

Step 4: Solve MPEC: For current iteration, MPEC (26) of each strategic WPP can be solved one by one as follows: when $MPEC_1$ is being solved, then strategy vectors of $MPEC_2, \dots, MPEC_i$ are kept fix and when $MPEC_2$ is being solved, strategy vectors of $MPEC_1, MPEC_3, \dots, MPEC_i$ are kept fix and so on.

Step 5: Check iteration counter: When strategy vector of each MPEC satisfy the stopping criterion $\|x_i^{(k+1)} - x_i^{(k)}\| \leq \varepsilon$, go to next step, otherwise update iteration counter by one and repeat pervious step. Else, for $k = K$, stop and display output as "Nash equilibrium solution not found".

Step 6: End

IV. RESULTS AND DISCUSSION

The proposed approach is illustrated by simulating different test cases on IEEE Reliability Test system, with 24 buses, 32 generating units, 17 demand and 38 transmission lines. For the sake of clarity on results, the installed capacity of generating units is assumed double and demand is assumed fifty percent higher than that reflected in corresponding Tables 7 and 5 of [14]. Demand is assumed elastic up to 10 percent. The range of demand prices offered lie within 40 to 120 \$/MWh. Three strategic wind power producers WPP1, WPP2 and WPP3 are considered connected at buses 22, 18 and 7 respectively. Installed capacity of producers WPP1, WPP2 and WPP3 is considered to be 300 MW, 400 MW and

600 MW, respectively. According to system configuration location and capacity of WPPs is analytically selected. The selection of both location and capacity would affect the network congestion as well as offering strategy of WPPs. WPP1, WPP2 and WPP3 are considered located at Beardstown, Carroll and Champaign, USA respectively. Each WPP has commercial 2.5 MW, ENERCON E-115 turbines installed at 139 m hub height. Number of installed turbines for each WPP is varied to reflect their capacity. Air density and temperature conditions are assumed same for each installed wind turbine. The used turbine model and its power curve are detailed in manufacturer database [15]. For all WPPs, actual wind speed data through January to June 2007 is considered, publically available at Illinois Institute of Rural Affair, USA [16]. Historical data of PJM balancing market is considered [17].

Uncertainty of wind power availability and balancing market prices are characterized through scenarios generated using ARIMA model. The estimated parameters [*i.e.* model order, autoregressive (AR) coefficient, moving average (MA) coefficient, variance of white noise (sigma)] of ARIMA model are shown in Table I. For accurate modeling of uncertainties, 5000 scenarios are generated and then reduced to 20 representative scenarios.

TABLE I
ARIMA MODEL PARAMETERS

Parameters	WPP1	WPP2	WPP3	Balancing market price
Order	(1,1,1)	(1,1,1)	(2,1,2)	(1,1,1)
AR1	-0.506	-0.410	0.687	0.748
AR2	-	-	0.222	0.991
MA1	-0.585	-0.500	0.600	-
MA2	-	-	0.400	-
Variance	0.936	0.952	0.526	0.959

In order to compare proposed approach, following test cases are considered.

Case I: *Base Case*: In this case, WPPs are considered non-strategic or price-takers. They offer their expected generation at zero price to day-ahead electricity market. ISO clears the market by solving market clearing problem (6)-(14), to provide cleared generation and LMP at each bus. WPPs can calculate their expected revenue according to their cleared generation and corresponding LMP. For each scenario, balancing market income/cost of WPPs is calculated according their surplus/deficit generation and balancing market price.

Case II: *Single Strategic WPP*: In this case, WPPs are considered price-makers, but at any given time only single WPP is active in day-ahead electricity market. Therefore, when particular WPPs behave strategically, other WPPs are assumed to behave non-strategically. Offering strategy of WPPs is developed by solving their MPECs (26). Rival behavior is not considered in this case.

Case III: *Multiple Strategic WPPs*: In this case, WPPs are considered price-maker and are active in day-ahead electricity market simultaneously. Strategic WPPs are required for the proposed EPEC approach (27) to develop their offering considering rival behavior.

Above test cases are simulated on Windows based laptop has a 1.67 GHz, Intel Core 2 duo processor and 2.50 GB RAM. Simulation for scenario generation and reduction has been performed on MATLAB platform and MPEC is solved using KNITRO 8.0 solver in GAMS software [18].

A. Single Period Results

For all considered test cases, the obtained results for first hour are shown in Table II. The demand factor for first hour is shown in Fig. 1.

TABLE II
BID PRICES (\$/MW), BID QUANTITIES (MW), EXPECTED PROFIT (\$), LMP (\$/MWh) FOR FIRST HOUR

	Bids/profit	Case I	Case II	Case III
WPP1	Price	0	48.91	25.35
	Quantity	105.31	172.76	150.47
	Profit	1270.77	1955.09	1998.66
WPP2	Price	0	45.22	25.34
	Quantity	54.55	225.37	295.66
	Profit	1536.71	2279.21	2452.47
WPP3	Price	0	46.06	60
	Quantity	195.03	324.71	437.72
	Profit	2147.32	2711.05	2548.96
LMP	-	40	[54.56, 45.22, 46.06]	60

From Table II, it is visualized that offered quantity bids of WPPs increase in Cases II and III, as compared to the base case. Increment and decrement in offered bid quantity of WPPs depend on their expected generation and balancing market prices. WPPs expecting balancing market price to be higher than day-ahead market would decrease their offer quantity in day-ahead electricity market and *vice-versa*. WPPs' offer prices in Cases II and III are equal to resulting LMP at the bus where they are located. Strategic WPPs can exercise their local market power capability and set LMP equal to their offered price. LMP is uniform for all buses without any network congestion.

As compared to the base case, expected profits earned by strategic WPPs, WPP1, WPP2 and WPP3 are respectively 53.85 %, 48.31 % and 26.25% higher than in Case II. In Case III, strategic WPPs develop their strategy using proposed approach. In this case, profit of WPP1 and WPP2 increases while profit of WPP3 decreases, as compared to Case II. WPP3 is located at Bus 7, and is connected to the system only through a transmission line *via* Bus 8. Therefore, market power of WPP3 is not effective in the presence of other strategic power producers, unless other lines are congested.

B. Multi Period Results

For a multi-period application of proposed approach, considered test cases are simulated for IEEE 24 bus system. As wind power is not controllable, simulations for each hour are carried out independently. Demand MW bids are varied according to demand factor profile shown in Fig. 1.

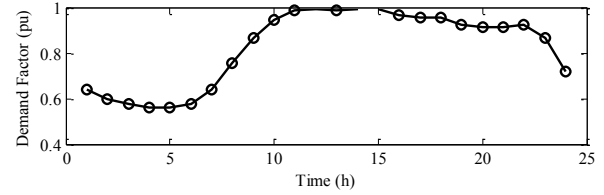


Fig. 1. Hourly demand factor (Source: Table 4, Column 4, [14])

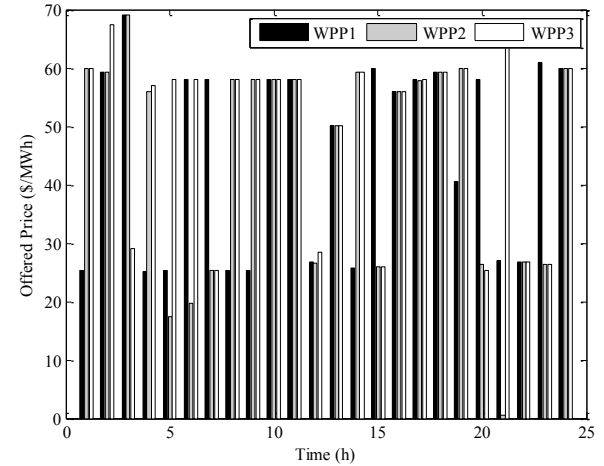


Fig. 2. Offered price bids of strategic WPPs in Case III

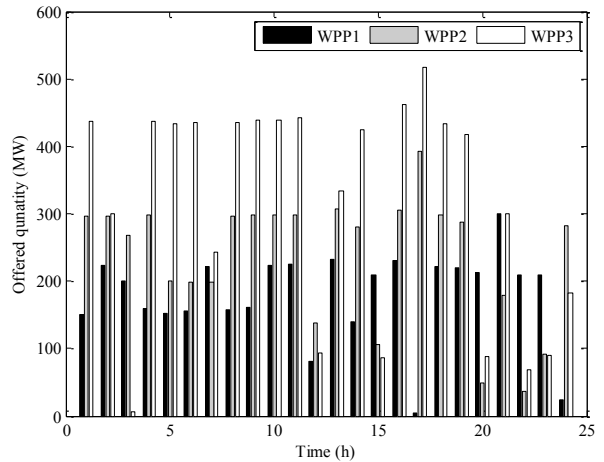


Fig. 3. Offered quantity bids of strategic WPPs in Case III

Hourly price and quantity bids to be offered by WPPs are shown in Figs. 2 and 3 respectively. Hourly profits earned by strategic WPPs are shown in Fig. 4. From these figures, it is visualized that power offered by strategic WPPs changes throughout the day. This is because of expected wind power generation and balancing market prices. In Hour 12 and last four hours, WPPs offer less power in the day-ahead market because in these hours balancing market prices are comparatively high. Therefore, WPPs try to sell their excess

generation in balancing market, rather than managing deficit generation by purchasing at higher prices. During each hour, except for hours 4, 5, 20 and 21, at least two power producers are active in day-ahead electricity market. Strategic behavior of WPPs also depends on network configuration and local demand, therefore during these hours only single WPP is active, which sets the market prices equal to their offered price.

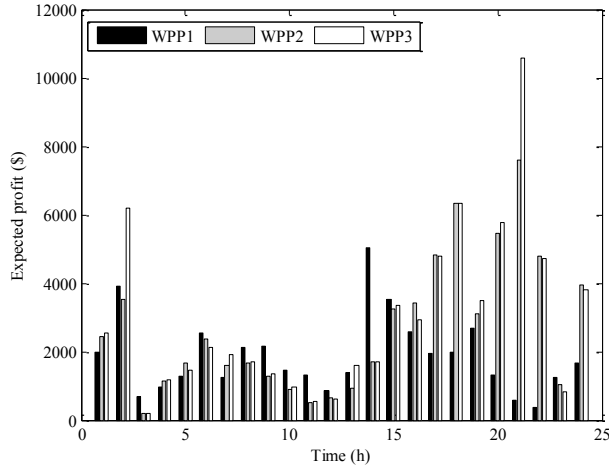


Fig. 4. Expected Profits of strategic WPPs in Case III

Finally, to evaluate the impact of transmission congestion on daily profit earned by WPPs, considered test cases are simulated again for IEEE-24 bus system, by assuming transmission line capacity equal to half of that considered in the original case of [14]. Daily profit of WPPs considering uncongested and congested networks is shown in Table III. From this it is visualized that profit of WPPs in Case I changes slightly. In Case II, expected profit of WPP1, WPP2 and WPP3 increase by 4.8%, 1.66% and 9.94 % respectively, due to transmission congestion. Expected profit of all WPPs decreases slightly in Case III, due to transmission congestion. Due to increment/ decrement in expected profits of WPPs throughout the day, percentage change in their daily profit is less as compared to their hourly profit.

TABLE III
DAILY EXPECTED PROFIT (\$) EARNED BY WPPS

	Uncongested network		
	Case I	Case II	Case III
WPP1	37953.74	44967.06	44796.49
WPP2	54609.76	58165.61	64367.51
WPP3	60949.62	63753.55	70652.73
	Congested network		
WPP1	39496.33	47129.52	44163.31
WPP2	53257.57	59133.19	60377.42
WPP3	58065.03	70095.89	69530.32

V. CONCLUSIONS

In oligopolistic day-ahead electricity markets, behavior of strategic WPPs is affected by rival behavior. Considering

rival behavior, offering strategy of strategic WPPs has been formulated using proposed stochastic EPEC approach. Proposed approach has been illustrated through practical case studies. Based on the obtained results, it is concluded that profit of strategic WPP would increase unilaterally when it offers its generation strategically, while other power producers behave non-strategically. However, in the presence of multiple strategic power producers, no producer can increase its profit unilaterally. Applicability of proposed approach on daily planning horizon and impact of transmission congestion on WPPs' strategies have been discussed. The proposed model can be improved by considering behavior of conventional generators and modeling demand uncertainty. Consideration of strategic behavior of wind power producers in intra-day and real-time markets are issues of further investigation.

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