Oligopolistic Behavior of Wind Power Producer in Electricity Markets including Demand Response Resources

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***Abstract*—This paper proposes an oligopolistic model for a wind power producer (WPP) with a market power to compete with other Gencos and take part in day-ahead, intraday and balancing markets. In order to model the mentioned oligopoly markets from WPP's viewpoint, a bi-level optimization framework is proposed based on multi-agent system and incomplete information game theory. In this context, the WPP participates in the intraday market where demand response resources are incorporated, to update its day-ahead offers. The problem uncertainties, i.e., wind power and market prices, are considered using a multi-stage stochastic programming approach. Because of these uncertainties, a well-known risk measurement, CVaR, is considered for problem optimization. Several numerical studies are accomplished and various aspects of the problem are analyzed. According to the obtained results, the proposed WPP model reveals that the prices of day-ahead and balancing markets could be increased due to the market power of WPP.**

Keywords—Demand Response, Oligopoly, Wind power producer.

I. NOMENCLATURE

Indices

i	index of Gencos
j	index of retailers
ω	index of scenarios

Parameters

$a_{i,\omega}, b_{i,\omega}, c_{i,\omega}$	coefficients of Genco's cost function
λ_t^k	offered price of block k of DRP
$D_{j,t}$	demand of retailer *j*
$e_{j,\omega}, f_{j,\omega}$	coefficients of retailers' income
MU_i, MD_i	minimum up and down times
r_t^+, r_t^-	positive and negative imbalance ratios
$W_{t,\omega}$	wind power production
SR_t	required spinning reserve
α	confidence level
β	weighting factor of taking risk
$\lambda_{i,\omega}^{up}, \lambda_{i,\omega}^{down}$	start-up and shut-down costs
π_ω	occurrence probability of scenario ω

Variables

B_ω	typical profit
$CDRP_{t,\omega}$	cost of DR related to DRP
$D_{j,t,\omega}^{DA}, D_{j,t,\omega}^{bal}$	day-ahead and balancing bids of retailer *j*
$DR_{t,\omega}$	amount of traded DR
$F_{t,k,\omega}, F_{t,k,\omega}^{cg}$	branch flow in normal and contingency states
$I_{i,t,\omega}$	commitment state of unit *i*
$P_{t,\omega}^{DA}, P_{t,\omega}^{bal}$	day-ahead and balancing WPP offers
$P_{i,t,\omega}^{DA}, P_{i,t,\omega}^{bal}$	day-ahead and balancing generations of Genco *i*
$P_{i,t,\omega}^{Res}$	offer of Genco *i* to the day-ahead reserve market
$P_{t,\omega}^{Sch}$	total scheduled power of WPP
$q_{t,\omega}^k$	scheduled power of block k of DRP
$y_{i,t,\omega}, z_{i,t,\omega}$	start-up and shut down binary variables
$\Delta_{t,\omega}$	total deviation of wind production
$\Delta_{t,\omega}^+, \Delta_{t,\omega}^-$	positive and negative deviations
$\lambda_{t,\omega}^{DA}, \lambda_{t,\omega}^{bal}, \lambda_{t,\omega}^{Res}$	day-ahead, balancing and reserve market prices
ξ	value-at-risk
η_ω	variable for computing CVaR

II. INTRODUCTION

Due to the increase in the energy consumption and environmental conservation concerns and decrease of fossil fuel resources, penetration of renewable resources has been significantly growing throughout the world. Among the renewable energies, wind power assigns a considerable share of the generation portfolio [1]. Therefore, these resources can play a dominant role in future of power system. Under this context, this paper proposes an offering strategy for a wind power producer (WPP) with market power that competes with other Gencos and participates in both of the day-ahead and balancing markets. On this basis, a stochastic decision making model is presented for participation of the WPP in day-ahead, intraday and balancing oligopoly electricity markets.

In this paper, in order to simulate the mentioned oligopoly markets from WPP's point of view, a bi-level optimization model is proposed based on multi-agent system and incomplete information game theory. The proposed method considers the Supply Function Equilibrium (SFE), one of the most accurate models for simulation of the game theory, to model the offering strategy of players.

Furthermore, transmission constraints may create opportunities for the market players to induce congestion to make an uncompetitive market [2]. Therefore, considering the network and security constraints in market simulation is very vital [3]. For this purpose, in this paper, a security constraint unit commitment (SCUC) method is utilized including AC power flow limits. In order to take part in the day-ahead market, the WPP is obligated to offer its generations to the day-ahead market one day in advance, with incomplete information about its hourly generations [4]. Despite undeniable advancements of wind forecasting, the day-ahead forecasts can cause the uncertainty of electricity systems and consequently imbalances costs to be increased. Utilization of DR [5], storage devices beside the wind farms [6], and joint operation of wind farms and hydro plants [7], are options presented to minimize the imbalances costs. However, Ref. [8] indicates that the option that has the highest flexibility and the lowest cost is Demand Response Resources (DRRs). On this basis, forming Demand Response eXchange market to mitigate WPPs' risk has been reported in [9]. Moreover, reducing the periods of wind forecast from day-ahead to intraday can drastically decrease the forecast errors and it has been proposed as another solution to overcome wind power uncertainties [10], [11].

Although offering strategy in day-ahead market and both of day-ahead and intraday markets have been respectively reported in [12], the mentioned reference has not considered the role of WPPs in oligopoly electricity markets. Even though in some recent papers oligopolistic behavior of WPPs has been studied [4], [13], other market players have been considered completely competitive, who offer to the market only based on their marginal costs. Moreover, in these reports the uncertainty of market players' behavior has not been addressed. Since the aim of WPP is to maximize the profit in all of the day-ahead, intraday and balancing markets, in this paper a three stage trading floor is proposed to cover the mentioned oligopoly markets. In addition to wind power uncertainties, WPPs should overcome the uncertainties of market prices. In this regard, a multi-stage stochastic programming approach is applied. Moreover, in order to represent the risk preferences of the WPPs, a risk management strategy should be considered. For this purpose, the risk aversion is implemented using limiting the deviations of expected profit by means of conditional value-at-risk (CVaR) technique [14].

The paper continues as follows: The formulation of the proposed strategic offering of WPPs is presented in Section II. Section III presents the oligopoly model of electricity market, the uncertainty characteristics and the multi-stage stochastic programming. Section IV is designated to numerical studies and Section V concludes the paper.

III. FORMULATION OF STRATEGIC OFFERING OF WIND POWER PRODUCERS

A. DR modeling

According to the benefits of DR programs in reliability and efficiency of power markets, the programs have been legalized and implemented in numerous countries [15]. To develop a market-based DR, a player called Demand Response Provider (DRP) is proposed.

The DRP aggregates the customers' responses to participate in the intraday electricity market. A description of the DRP price-quantity is formulated in (1)-(3).

$$DR_{t,\omega} = \sum_{k=1}^{NQ} q_{t,\omega}^{k} \tag{1}$$

$$CDRP_{t,\omega} = \sum_{k=1}^{NQ} \lambda_t^{Intra} q_{t,\omega}^{k} \tag{2}$$

$$DR_{t,\omega} \le DR_t^{\max} \tag{3}$$

B. Incorporating risk control (CVaR)

In this paper, CVaR is considered to demonstrate the integrated risk management problem of a WPP. The amount of α is assigned to 0.95. The formulation of CVaR can be expressed as (4)-(6) [1].

$$Max \;\; B_{\omega} = \quad \xi - \frac{1}{1-\alpha}\sum_{\omega=1}^{\Omega_N} \pi_{\omega}\eta_{\omega} \tag{4}$$

$$-B_{\omega} + \xi - \eta_{\omega} \le 0 \tag{5}$$

$$\eta_{\omega} \ge 0 \tag{6}$$

The value of η_{ω} is set to 0 if the profit of scenario ω is higher than ξ. For the remaining scenarios, η_{ω} are assigned to the difference between ξ and the related profit. The constraints (5) and (6) are utilized to unify the risk-metrics CVaR.

C. Objective function

The objective function of a WPP is maximizing the expected profit that can be expressed as:

$$\begin{aligned} &\text{Max}\{Expected \;\; Profit\} = \\ &\sum_{\omega=1}^{\Omega_N} \pi_{\omega} \sum_{t=1}^{T} \begin{bmatrix} \lambda_{t,\omega}^{DA} P_{t,\omega}^{DA} \\ -CDRP_{t,\omega} \\ +\lambda_{t,\omega}^{bal} P_{t,\omega}^{bal} + \lambda_{t,\omega}^{DA} r_t^{+} \Delta_{t,\omega}^{+} - \lambda_{t,\omega}^{DA} r_t^{-} \Delta_{t,\omega}^{-} \end{bmatrix} \\ &\quad + \beta\left(\xi - \frac{1}{1-\alpha}\sum_{\omega=1}^{\Omega_N} \pi_{\omega}\eta_{\omega} \right) \end{aligned} \tag{7}$$

The first term in (7) represents the WPP incomes achieved from trading energy with the day-ahead market. The second term is the cost of purchasing DR from intraday market. The third term denotes the WPP incomes resulted from trading energy in the balancing market. The next two terms represent positive and negative imbalance costs, respectively. Finally, the last term of the objective function is related to risk modeling and it indicates the CVaR multiplied by β. β=0 denotes a risk-taker WPP and β=1 represents a risk-averse one. The other considered constraints of the problem are expressed as below:

$$0 \le P_{t,\omega}^{DA} \le P^{\max} \tag{8}$$

$$P_{t,\omega}^{Sch} = P_{t,\omega}^{DA} + P_{t,\omega}^{bal} - DR_{t,\omega} \tag{9}$$

$$0 \le P_{t,\omega}^{Sch} \le P^{\max} \tag{10}$$

$$\Delta_{t,\omega} = W_{t,\omega} - P^{Sch}_{t,\omega} \quad (11)$$

$$\Delta_{t,\omega} = \Delta^{+}_{t,\omega} - \Delta^{-}_{t,\omega} \quad (12)$$

$$0 \le \Delta^{+}_{t,\omega} \le W_{t,\omega} \quad (13)$$

$$0 \le \Delta^{-}_{t,\omega} \le P^{\max} \quad (14)$$

Inequality (8) imposes that the offers in day-ahead market should not be higher than the generation capacity of units installed in the wind farm, P^{max}. The total scheduled energy of WPP in all of the day-ahead, intraday and balancing markets is shown in (9). Inequality (10) limits the total scheduled energy. Eqs. (11) and (12) are utilized to calculate the total energy deviation using the last scheduled energy. The bounds impose on the positive and negative deviations are given by (13) and (14). By applying the objective function to (5), the formulation of incorporating risk can be obtained as (15).

$$-\sum_{t=1}^{T}\begin{bmatrix} \lambda^{DA}_{t,\omega} P^{DA}_{t,\omega} \\ -CDRP_{t,\omega} \\ +\lambda^{bal}_{t,\omega} P^{bal}_{t,\omega} + \lambda^{DA}_{t,\omega} r^{+}_{t} \Delta^{+}_{t,\omega} - \lambda^{DA}_{t,\omega} r^{-}_{t} \Delta^{-}_{t,\omega} \end{bmatrix} + \xi - \eta_{\omega} \le 0 \quad (15)$$

IV. MODELING THE OLIGOPOLY ELECTRICITY MARKET FROM WIND POWER PRODUCER'S VIEWPOINT

In this paper, aiming to improve the reality of the studies, the electricity market is modeled as an oligopoly market instead of being perfectly competitive. For this purpose, a multi-agent environment based on bi-level optimization has been developed. The agents do not have information of their competitors. Hence, the mentioned environment for the WPP becomes an incomplete information game theory [2]. The details of the proposed electricity market model from the WPP's viewpoint are expressed as follows:

A. Market players

In the proposed agent-based model, each market player (e.g., Gencos and retailers) is independently modeled using agents, so that their objective functions correspond to maximizing their profit, participating in day-ahead and balancing markets. The objective function of each Genco agent can be formulated as follows:

$$\text{Max}\{Expected\ \ Profit\} = \sum_{\omega=1}^{\Omega_N} \pi_{t,\omega} \sum_{t=1}^{T} \left\{ \begin{array}{l} P^{DA}_{i,t,\omega}\lambda^{DA}_{t,\omega} + P^{bal}_{i,t.\omega}\lambda^{bal}_{t,\omega} + P^{Res}_{i,t,\omega}\lambda^{Res}_{t,\omega} \\ -\left(a_{i,\omega}P^{2}_{i,t,\omega} + b_{i,\omega}P_{i,t,\omega}\right) - c_{i,\omega}I_{i,t,\omega} \\ -\lambda^{up}_{i,\omega} y_{i,t,\omega} - \lambda^{down}_{i,\omega} z_{i,t,\omega} \end{array} \right\} \quad (16)$$

subject to:

$$P_i^{\min} I_{i,t,\omega} \le P_{i,t,\omega} \le P_i^{\max} I_{i,t,\omega} \quad (17)$$

$$I_{i,t,\omega} - I_{i,t-1,\omega} = y_{i,t,\omega} - z_{i,t,\omega} \quad (18)$$

$$y_{i,t,\omega} + z_{i,t,\omega} \le 1 \quad (19)$$

$$y_{i,t,\omega} + \sum_{j=1}^{MU_i - 1} z_{i,t+j,\omega} \le 1 \quad (20)$$

$$z_{i,t,\omega} + \sum_{j=1}^{MD_i - 1} y_{i,t+j,\omega} \le 1 \quad (21)$$

$$P_{i,t,\omega} - P_{i,t-1,\omega} \le RU_i + P_i^{\min} y_{i,t,\omega} \quad (22)$$

$$P_{i,t-1,\omega} - P_{i,t,\omega} \le RD_i + P_i^{\min} z_{i,t,\omega} \quad (23)$$

where $P^{bal}_{i,t,\omega} + P^{DA}_{i,t,\omega} = P_{i,t,\omega}$.

Inequality (17) denotes the unit output limits. Constraints of minimum up and down times are linearly expressed in (18)-(21). Constraints of unit ramp up and ramp down are presented in (22) and (23), respectively.

Retailers are the other considered market players. The objective function of each retailer can be formulated as follows:

$$\text{Max}\{Expected\ \ Profit\} = \sum_{\omega=1}^{\Omega_N} \pi_{t,\omega} \sum_{t=1}^{T} \left\{ -D^{DA}_{j,t,\omega}\lambda^{DA}_{t,\omega} - D^{bal}_{j,t,\omega}\lambda^{bal}_{t,\omega} + e_{j,\omega} + f_{j,\omega} D_{j,t} \right\} \quad (24)$$

where $D^{DA}_{j,t,\omega} + D^{bal}_{j,t,\omega} = D_{j,t}$.

All agents utilize the prices of electricity markets obtained from simulating the previous iteration of clearing the transactions of market. After that, each agent maximizes its profit by using the mentioned prices to obtain the optimal amount of bid/offer in each hour of next iteration. Afterward, the agents generate their bidding/offering strategies by applying the optimal quantity and price using supply function equilibrium (SFE) model [2]. Therefore, each player uses the SFE vector (α^{SFE}, β^{SFE}) to submit its offers/bids to the markets.

B. Clearing the electricity market transactions

In order to model the behavior of WPPs in a specific period, in this paper, instead of optimal power flow (OPF), the role of ISO in day-ahead horizon in clearing the electricity market and determining auction winners has been defined using a security constrained unit commitment (SCUC) problem [3], which maximizes social welfare considering security constraints. The SCUC problem maximizes the offer-based social welfare as expressed in (25). In addition, the objective of ISO in balancing market is accomplished by a security constraint economic dispatch as presented in (26). From ISO's point of view, some other constraints should be considered as presented below:

$$\text{Max}\{Social\ \ Welfare\} = \left\{ \sum_{t=1}^{T} \left(\sum_{j \in Retailers} D^{DA}_{j,t,\omega}\lambda^{DA}_{t,\omega} - \sum_{i \in Gencos} \left(P^{DA}_{i,t,\omega}\lambda^{DA}_{t,\omega} + P^{Res}_{i,t,\omega}\lambda^{Res}_{t,\omega} \right) \right) \right\} \quad (25)$$

$$\text{Max}\{Social\ \ Welfare\} = \left\{ \sum_{t=1}^{T} \left(\sum_{j \in Retailers} D^{bal}_{j,t,\omega}\lambda^{bal}_{t,\omega} - \sum_{i \in Gencos} P^{bal}_{i,t,\omega}\lambda^{bal}_{t,\omega} \right) \right\} \quad (26)$$

$$\sum_{j \in Retailers} D_{j,t,\omega}^{DA} = \sum_{i \in Gencos} P_{i,t,\omega}^{DA} \tag{27}$$

$$\sum_{j \in Retailers} D_{j,t,\omega}^{bal} = \sum_{i \in Gencos} P_{i,t,\omega}^{bal} \tag{28}$$

$$\sum_{i \in Gencos} P_{i,t}^{\max} I_{i,t,\omega} = \sum_{j \in Retailers} D_{j,t} + SR_t \tag{29}$$

$$-F_k^{\max} \le F_{t,k,\omega} \le F_k^{\max} \tag{30}$$

$$-F_k^{\max} \le F_{t,k,\omega}^{cg} \le F_k^{\max} \tag{31}$$

Eqs. (27) and (28) ensure the balance between supply and demand. The required spinning reserve is expressed in (29). Inequalities (30) and (31) consider the network limits in normal and contingency states, respectively. The applied formulation of power flow calculation has been presented in [3].

In the model, each agent receives the daily prices of energy and reserve markets from the previous iteration. Each above-mentioned agent solves its self-scheduling problem and offers/bids to the electricity markets by SFE pairs. Then, the economic solution for the participant agents in the markets is achieved including auction winners, quantities, prices of energy and reserve markets.

C. Stochastic Programming Approach

In this paper, two major sets of uncertainty are considered namely; *wind uncertainty* and *market uncertainty*. Modeling the aforementioned uncertainties is expressed as following:

The distribution function of wind speed is usually considered using a Weibull distribution [16]. To this end, the probability distribution function of wind speed can be utilized to obtain produced wind power. Moreover, the market prices are characterized by lognormal distribution in each hour [17].

Different realizations of the wind power generation and market prices are modeled using the scenario generation process based on roulette wheel mechanism (RWM) [18].

In order to consider the impact of both sources of uncertainty mentioned above on the strategic behavior of wind power producer, they have been characterized as stochastic procedures and the WPP problem has been solved using a three-stage stochastic programming approach. In the proposed approach, each stage denotes a market session. The classification of decision variables of each stage is presented as follows:

1) The first stage (*here-and-now*) stochastic decision variables are ($a_{i,\omega}, b_{i,\omega}$, $c_{i,\omega}$, $e_{j,\omega}$, $f_{j,\omega}, D_{j,t,\omega}^{DA}$, $I_{i,t,\omega}$, $P_{t,\omega}^{DA}$, $P_{i,t,\omega}^{DA}$, $P_{i,t,\omega}^{Res}$, $P_{t,\omega}^{Sch}$, $y_{i,t,\omega}$, $z_{i,t,\omega}$, $\lambda_{t,\omega}^{DA}$ and $\lambda_{t,\omega}^{Res}$).

2) Stochastic variables ($CDRP_{t,\omega}, DR_{t,\omega}$ and $q_{t,\omega}^{k}$) are the second stage (*wait-and-see*) variables.

3) The third stage (*wait-and-see*) stochastic decision variables are ($W_{t,\omega}$, $D_{j,t,\omega}^{bal}$, $P_{t,\omega}^{bal}$, $\Delta_{t,\omega}$, $\Delta_{t,\omega}^{+}$, $\Delta_{t,\omega}^{-}$ and $\lambda_{t,\omega}^{bal}$).

V. NUMERICAL STUDIES

The proposed model has been evaluated by using a modified IEEE 30-bus test system consisting of a 50 MW wind farm and 4 thermal plants.

The Swift Current wind data is utilized for the wind farm [19]. Based on the *wait and see* technique, different wind power series are obtained for day-ahead, intraday and balancing horizons. The intervals between minimum and maximum amount of the uncertain parameters for day-ahead and intraday markets are demonstrated in Fig. 1. Moreover, three retailers have been added to this system to retail the electricity to consumers. It should be noted that, intervals 1 to 9am, 10am to 7pm and 8 to 12pm have been respectively considered as low load, off-peak, and peak periods.

In order to investigate the impact of the proposed model, the locational marginal prices (LMPs) of Bus 5 achieved from two cases have been compared namely; considering completely competitive day-ahead and balancing markets; and considering oligopoly markets. The LMPs of the mentioned cases have been indicated in Figs. 2 and 3.

As it can be seen from Figs. 2 and 3, when WPP participates in completely competitive day-ahead and balancing markets, it is required to trade more in the intraday market to insure its profit. Because of the increase of DR, the price of intraday market is increased. In addition, the averages of LMPs in both the day-ahead and balancing markets are increased because of power market of the WPP. In order to show the effect of DR on WPP's profit, the results obtained from two cases, i.e., without and with intraday market are depicted in Figs. 4 and 5, respectively. The imbalance ratios have been supposed to be equal to 1.2 and 0.8. The amount of β is assigned to 0 that is related to a risk-taker WPP. It can be observed that, enabling DR can take the opportunity for WPP to increase significantly its balancing income in most of hours and accordingly to increase its total profit.

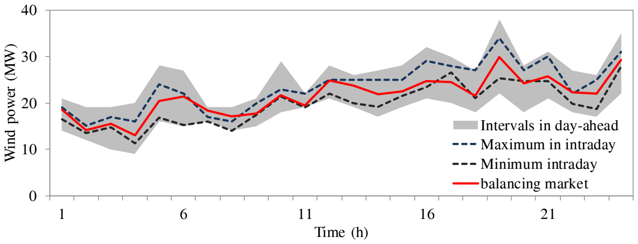

Fig. 1. Wind power intervals in different market horizons

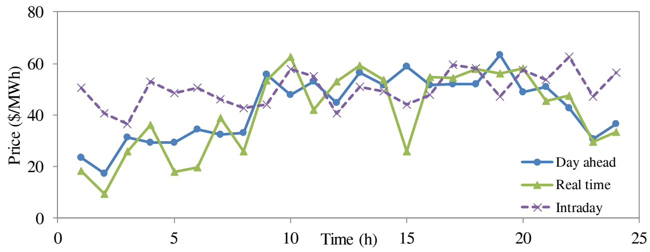

Fig. 2. LMPs of bus 5 considering completely competitive market.

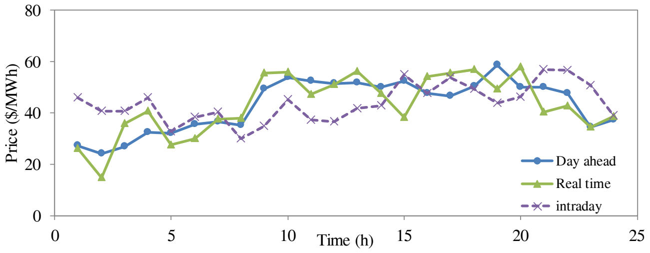

Fig. 3. LMPs of bus 5 considering oligopoly market.

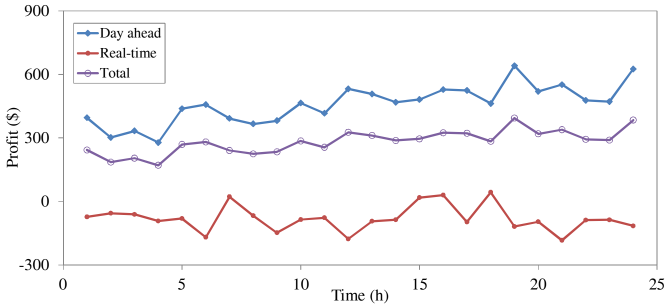

Fig. 4. WPP's profits without participating in the intraday market.

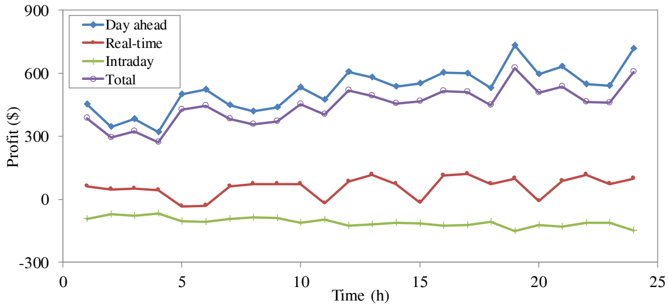

Fig. 5. WPP's profits with participating in the intraday market.

TABLE I
WPP'S COSTS AND REVENUES FOR DIFFERENT LEVELS OF DRP PARTICIPATION

DRP participation levels	0%	10%	20%	30%
Day-ahead market income ($)	11010	12606	12901	13022
Intraday market cost ($)	0.00	2600	2670	2689
Balancing market income ($)	-2042	1712	1782	1791
Imbalance cost ($)	2208	1006	1011	1013
CVaR ($)	6237	10165	10374	10403
Expected profit ($)	6759	10712	11001	11110
Profit increase (%)	-	58.48	62.76	64.37

The effect of DRP participation level in the intraday market on WPP's profits has been investigated in Table I. With increasing the participation of DRPs, the WPP prefers to participate in the intraday market to modify its offers. As can be observed, the increase in DRP participation level causes significant increases in the WPP's expected profits up to 10% of DRP participation level. After that, the impact of the intraday market on the WPP's profit is decreased due to WPP's installed capacity; thus, the tendency of WPP for participating in the intraday market is saturated.

VI. CONCLUSION

This paper proposed a model of WPP in oligopoly day-ahead, intraday and balancing electricity markets. The uncertain nature of wind power and market prices were modeled using multi-stage stochastic programming. Furthermore, conditional value at risk was applied as a risk measure that WPP can specify its desirable weighting between the expected profit and risk. The results indicated that with increasing the DRRs, the WPP had more participation in the intraday market to modify its offers. The proposed oligopoly model of WPP in comparison to a completely competitive one indicated that prices of day-ahead and balancing markets could increase due to WPP's market power. This revealed the necessity of modeling WPPs in oligopolistic form in power systems with high penetration of wind power.

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