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Abstract—**Recent restructure and expansion of electric network enabled the end-use customers to participate in local energy markets by managing their consumption/production. In this context, this paper proposes a mathematical approach for price maker WPP offering strategy with considering risk criteria. In fact, to assess risk aversion behavior of the WPP, CVaR as a measurement tool is implemented in the problem considering transactions and expected profit. Finally, an assessment framework is established to evaluate the benefits of implementing DR programs on the energy costs and the individual profit of the WPP. Also, effective metrics are implemented to the problem to evaluate the effect of implementing DR programs on the market power of the WPP. The results show that with implementing DR actions, the electricity price in most hours remained the same which implies the reduction in market power of the WPP.**

Keywords—Demand side management, electricity market, market power, responsive load, wind power producer (WPP).

I. Introduction

During the last years, there has been a significant increase in the capacity of renewable resources installed all around the world. With increasing the number and size of wind producers, the subsidies and grants given to the renewables enhanced substantially [1]. Moreover, wind power producers (WPPs) tend to sell their power in a competitive trading floor instead of through power purchasing at fixed prices within different contracts [2]. In that study, the authors used a bilateral contract to control the risks of the problem; however, no mathematical problem is used in the formulation. In such conditions, the WPPs should handle the uncertainties related to their wind generation and also the uncertainties of electricity markets. To control these uncertainties, different optimization models have been used for WPPs in the literatures. In [3], a stochastic optimization model for generating the optimal price-maker trading strategy for a WPP using virtual bidding, which is a kind of financial tool available in most electricity markets of the United States is presented. In that model, virtual bidding is used to improve the WPP's market power in the day-ahead (DA) market by trading at multiple buses, which are not limited to the locations of the wind units.

Increment in the penetration level of wind energy all around the world could influence the results of market clearing problems, in which, the WPPs are modelled as price maker agents through bi-level optimization problems [4]. In [5], the strategic WPP makes contract with DR aggregators to reduce the risk natured from its production. In different studies, demand response (DR), energy storage systems, bilateral contracts and other opportunities are implemented to improve the expected profit of the WPP [6]. DR can be considered as a cost-effective method in order to enable implementing of large-scale renewable resources in the network [7]. There are different literatures developing the fair potential of DR integrated in to the current electricity market [8].

The WPP submits its wind power in DA market strategically, while, the WPP should cover its energy deviations in real time market. Be noted that since the WPP does not have an elastic power deviation, the WPP does not participate in real time market strategically and it behaves as a price-taker [9]. The rapid development of renewables transforms many of electrical consumers into prosumers [10]. The main objective of a traditional passive distribution network is to supply the end-use customers through transmission network. With restructuring during the recent years, the renewable resources were incorporated to the passive network and changed it into an active system. In such active framework, the end-use customers can consume, produce and even store energy in the distribution level. Furthermore, to mitigate the energy costs and also to promote the utilization of the green resources, peer to peer (P2P) energy trading has been studied in different papers [11]. Moreover, the effect of DR participants on the strategic behavior of decision makers is under focused. In [12], the effect of only demand shifting in mitigating the market power by the generation side has been provided.

Here, a stochastic-bi-level optimization model is presented for a price maker WPP who behaves strategically in DA market. Moreover, DR scheme is applied to the problem as a financial option. In addition, the effect of demand side management in mitigating the market power of the strategic WPP is investigated. From the viewpoint of risk measurement tools, the influence of risk management of the WPP on the energy exchanges of the problem is also assessed.

This paper is prepared as follows. The problem description is provided in Section II. The formulation is given in Section III. Then, the analysis and numerical results are

shown in Section VI and the conclusion is provided in Section V.

II. Strategic Offering of a Wind Power Producer in the DA Market

With increasing the penetration of renewables in the network, the owner of those resources would participate in the market as price makers. In such conditions, the WPP submits its offers in DA market for several hours of the next day and then, it enters the balancing markets for corrective actions. As it seems rational, the WPP should sell its excess of generation cheaper than the DA market prices and purchase its energy shortage more expensive than the DA prices. In addition, it is supposed that the WPP has a bilateral contract with a small industrial load. Therefore, the secure operation of the problem should be ensured with considering technical secure operation of the bilateral contract and the rest of the elements.

On the other hand, the network operator clears the market-clearing problem in order to obtain the prices and give the schedule of consumption and production. This multi-agent problem is modelled with a bi-level optimization framework, in which the WPP as decision maker do not have information of its competitors. Hence, this bi-level problem is considered as an incomplete information game theory. To manage the risk of alternative nature of renewables in a smart grid, it is required to utilize the flexibility behavior of prosumers. Moreover, in a smart grid, the prosumers are capable to adjust their consumption through communication signals. In such a restructured network, lack of price-responsive loads and the lack of experience in the market level, makes the determination of competitive prices sever. Consequently, with respect to the market power issues, different measurement tools are adopted to measure market power of different resources. After that, it would be possible for the market operator to find various ways to mitigate the market power of those strategic agents. On the other hand, augmenting the responsiveness of demand side is surely a prominent way toward reducing the market power of strategic producers as it was mentioned in the previous literatures [12].

In this paper, there are different sources of uncertainties that affect the results of the problem that are characterized through multiple scenarios. The uncertainties related to the market prices, loads and renewable generations are accounted via stochastic programming.

III. Mathematical Model for Strategic Offering of Wind Power Producer

A. The Bi-level Arbitrage Model of the WPP

The main objective of the WPP is maximization of its expected profit that is described with the following objective function:

$$Max \sum_{\omega\in\Omega}\pi_\omega \sum_{t\in T}\begin{bmatrix} E^{cl}_{t,\omega}\rho^{DA}_{t,\omega} - E^{P}_{t,\omega}\rho^{P}_{t} + E^{bil}_{t,\omega}\rho^{bil}_{t} \\ E^{dn}_{t,\omega}\rho^{dn}_{t,\omega} - E^{up}_{t,\omega}\rho^{up}_{t,\omega} \end{bmatrix} + \beta(\xi - \frac{1}{1-\alpha}\sum_{\omega=1}^{\Omega}\pi_\omega\eta_\omega) \quad (1)$$

The cleared power of the WPP must be equal to the predicted wind power and the compensated power in the regulating market as in (2). Moreover, the wind power generation is limited within its maximum capacity as in (3).

$$E^{P}_{t,\omega} - E^{bil}_{t,\omega} - E^{dn}_{t,\omega} + E^{up}_{t,\omega} = E^{cl}_{t,\omega} \quad (2)$$

$$E^{p}_{t,\omega} \le \overline{E}_W \quad (3)$$

$$\sum_{\omega\in\Omega}\pi_\omega \sum_{t\in T}\begin{bmatrix} E^{cl}_{t,\omega}\rho^{DA}_{t,\omega} - E^{P}_{t,\omega}\rho^{P}_{t} + E^{bil}_{t,\omega}\rho^{bil}_{t} \\ E^{dn}_{t,\omega}\rho^{dn}_{t,\omega} - E^{up}_{t,\omega}\rho^{up}_{t,\omega} \end{bmatrix} + \eta_\omega - \xi \ge 0 \quad (4)$$

$$\eta_\omega \ge 0 \quad (5)$$

Moreover, the expressions of (4) and (5) denote the risk aversion constraints.

In the lower level, the DSO tends to maximize the social welfare as in (6). The energy balance at each node should be satisfied as in (7) such that the power flow of each line is denoted in (8) that is limited based on (9). The limitation of demand and generation are also stated in (10) and (11). Constraint (12) expresses that cleared power in DA market is restricted with its offering values. In (13), the limitation of the voltage angle is stated and finally, the fixed reference voltage angle is given in (14).

$$Min \sum_{\omega\in\Omega}\pi_\omega \sum_{t\in T}\left[E^{G}_{t,\omega}\rho^{G} + \alpha^{W}_{t}E^{cl}_{t,\omega} - E^{D}_{t,\omega}\rho^{D}_{t,\omega}\right] \quad (6)$$

$$\sum_{G\in NG} E^{G}_{t,\omega} + E^{cl}_{t,\omega} - \sum_{D\in ND} E^{D}_{t,\omega} - \sum_{k|s(k)=n} f_k + \sum_{k|r(k)=n} f_k = 0 \quad (7)$$

$$f_k = B_k(\delta_{s(k)} - \delta_{r(k)}) \quad (8)$$

$$-f^{\max}_k \le f_k \le f^{\max}_k \quad (9)$$

$$0 \le E^{D}_{t,\omega} \le \overline{E}_D \quad (10)$$

$$0 \le E^{G}_{t,\omega} \le \overline{E}_G \quad (11)$$

$$0 \le E^{cl}_{t,\omega} \le E^{of}_{t,\omega} \quad (12)$$

$$-\pi \le \delta_n \le \pi \quad \forall n \setminus n: ref \quad (13)$$

$$\delta_n = 0 \quad n: ref \quad (14)$$

Using AC optimal power flow (ACOPF) or DC optimal power flow (DCOPF), the LMP would be attained; although, DCOPF is widely used in the papers due to its computational efficiency and approximation accuracy [13]. From the lower level problem, the LMPs would be obtained and from the upper level one, the scheduling foe energy exchange of loads and generators would be achieved. More details can be found in [13].

The bi-level problem as a mathematical problem with equilibrium constraints (MPEC) would be transformed to a single level one using Karush-Kuhn-Tucker (KKT) optimality conditions as complementarity constraints. Then, with using duality theory the MPEC would be changed to a mixed-integer linear programming (MILP) framework which can be solved with commercial packages.

B. Single Level Model of the Problem

Based on the continuity and convexity of the lower level, it can be replaced with the corresponding KKT optimality constraints [15]. The obtained KKT optimality conditions of the lower level problem are provided here as:

$$\rho^{G} - \rho_{n,t,\omega} - \varepsilon_{G}^{\min} + \varepsilon_{G}^{\max} = 0 \quad (15)$$

$$\alpha_{t}^{W} - \rho_{n,t,\omega} - \varepsilon_{W}^{\min} + \varepsilon_{W}^{\max} = 0 \quad (16)$$

$$\rho_{t,\omega}^{D} - \rho_{n,t,\omega} - \varepsilon_{D}^{\min} + \varepsilon_{D}^{\max} = 0 \quad (17)$$

$$\rho_{n(s),t,\omega} - \rho_{n(r),t,\omega} - \beta_{k} - \beta_{k}^{\min} + \beta_{k}^{\max} = 0 \quad (18)$$

$$\sum_{k|s(k)=n} B_k \beta_k - \sum_{k|r(k)=n} B_k \beta_k - \mu_n^{\min} + \mu_n^{\max} = 0, \forall n \setminus n : ref \quad (19)$$

$$\sum_{k|s(k)=n} B_k \beta_k - \sum_{k|r(k)=n} B_k \beta_k - \gamma_n = 0, \quad n : ref \quad (20)$$

$$0 \le \beta_{k}^{\max} \perp f_{k}^{\max} - f_{k} \ge 0 \quad (21)$$

$$0 \le \beta_{k}^{\min} \perp f_{k} + f_{k}^{\max} \ge 0 \quad (22)$$

$$0 \le \varepsilon_{D}^{\max} \perp \overline{E}_{D} - E_{t,\omega}^{D} \ge 0 \quad (23)$$

$$0 \le \varepsilon_{D}^{\min} \perp E_{t,\omega}^{D} \ge 0 \quad (24)$$

$$0 \le \varepsilon_{G}^{\min} \perp E_{t,\omega}^{G} \ge 0 \quad (25)$$

$$0 \le \varepsilon_{G}^{\max} \perp \overline{E}_{G} - E_{t,\omega}^{G} \ge 0 \quad (26)$$

$$0 \le \varepsilon_{W}^{\max} \perp E_{t,\omega}^{of} - E_{t,\omega}^{cl} \ge 0 \quad (27)$$

$$0 \le \varepsilon_{W}^{\min} \perp E_{t,\omega}^{cl} \ge 0 \quad (28)$$

$$0 \le \mu_{n}^{\max} \perp (\pi - \delta_{n}) \ge 0, \quad \forall n \setminus n : ref \quad (29)$$

$$0 \le \mu_{n}^{\min} \perp (\pi + \delta_{n}) \ge 0, \quad \forall n \setminus n : ref \quad (30)$$

In the above equations, $\varepsilon_{D}^{\min}$, $\varepsilon_{W}^{\max}$, $\varepsilon_{W}^{\min}$, $\varepsilon_{G}^{\max}$, $\varepsilon_{G}^{\min}$, $\varepsilon_{D}^{\max}$, $\beta_{k}^{\min}$, $\mu_{n}^{\min}$, $\beta_{k}^{\max}$,are the Lagrangian γ_{n} , $\mu_{n}^{\max}$ variables.

C. Demand Side Model

In order to show the relation between price and demand of the responsive loads, the relation between the initial load (E_{t}^{int} and the adjusted load (E_{t}) is considered with the following expression:

$$E_{t} = E_{t}^{\text{int}} \exp \sum_{h \in T} Elas_{t,t} \ln[\frac{\rho_{n,t,\omega}}{\rho_{t}^{D,\text{int}}} + \frac{1}{1 + Elas_{t,t}^{-1}}] \quad (31)$$

Where, $Elas_{t,t}$ denotes elasticity of demand of customers, $\rho_{t}^{D,\text{int}}$ is the average of DA price ($\rho_{n,t,\omega}$). More details can be found in [15].

IV. Case Study

In this section, an illustrative test system is demonstrated to show the performance of the proposed trading decision making problem for the WPP with the total predicted wind power given in Fig. 1. Here, it is considered that the WPP supply the bilateral load in Fig. 2. In this study, a daily time horizon with 24 hours is assumed in which it is considered that the loads bid their demands across the whole day with time variant prices. The total required load of the network is shown in Fig. 3. The problem is applied to IEEE 33 bus test system and it is solved using GAMS software [16].

The electricity market prices are also depicted in Fig. 4. Technical characteristics of generation units are extracted from [2]. These DGs are located in buses #8, 13, 16 and 25. Moreover, in these buses, there exists some prosumers with some responsive loads which also own some photovoltaic systems.

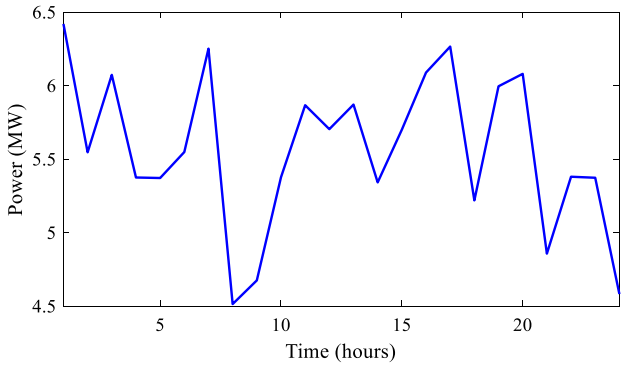

Fig. 1 Predicted wind power production.

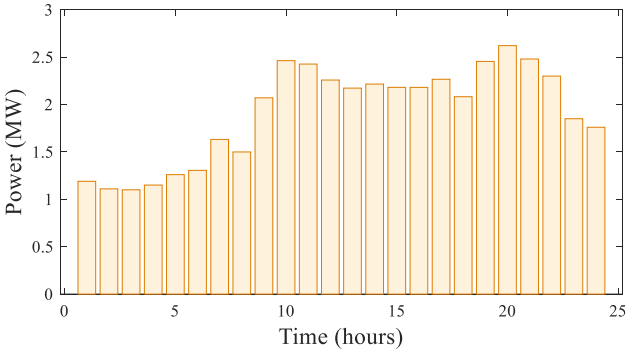

Fig. 2 Bilateral load supplied by the WPP.

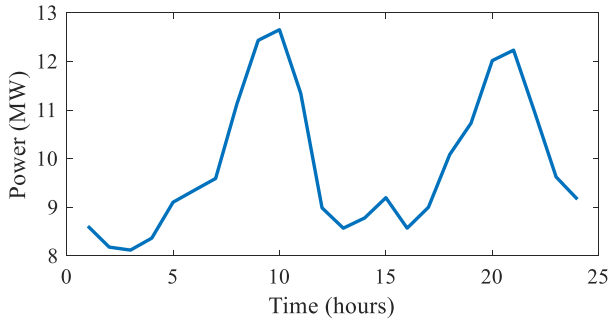

Fig. 3 Total load of the network.

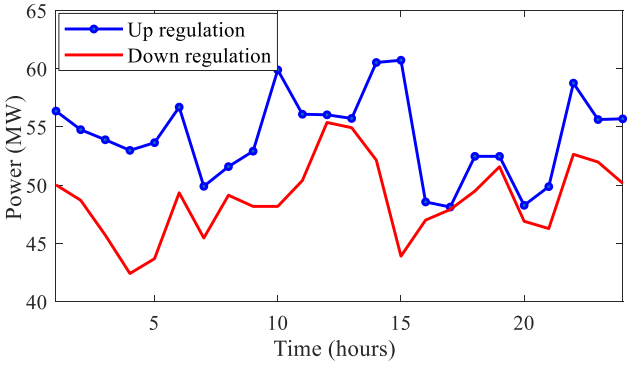

Fig. 4 Regulation market prices.

The expected profit of the WPP versus CVaR in DR=40% and in different β values is provided in Fig. 5. As expected, with increasing β, the scenarios that are far from the mean value of the expected profit would be ignored and the WPP behaves more risk aversely. In this case, the expected profit reduces, while the CVaR value augments.

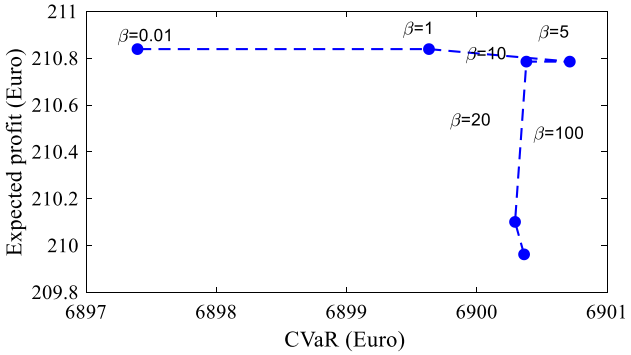

Fig. 5 Expected profit versus CVaR in DR=40% and different β values.

The Energy of the WPP sold and cleared in DA market in β=1 and in different DR participants is given in Fig. 6. As expected, the WPP offers strategically in order to take advantage aiming at the maximization of its profit. In such conditions, when the loads adjust their demand, the load reduction would be realized and so, the WPP can sell its wind power to DA market. In this case, the cleared energy of the WPP with increasing DR participants increases.

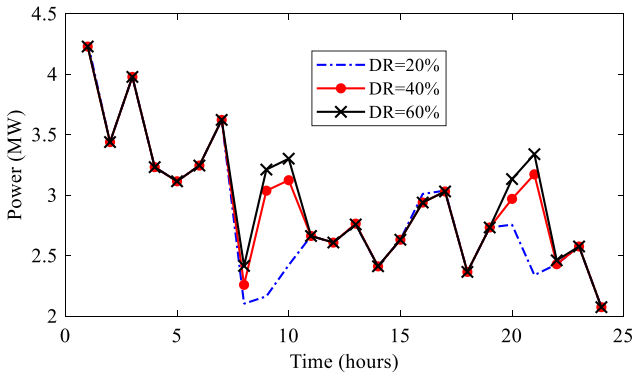

Fig. 6 Wind power sold in DA market by the WPP.

In this problem, there exist multiple producers, prosumers and consumers who attempt to attain the optimal pricing. One interesting observation from the price signal is that the trend of the price is affected from both offering price of DG units and bidding price of loads. With increasing DR participants, the value of selling price augments. That is because with implementing DR programs, the lower energy dispatch surely reduces the profit. So, the cleared price augments to compensate the loss of losing loads. In fact, with implementing DR actions, the electricity price in most hours remained the same which implies the reduction in market power of the WPP. Although, to keep the profit of the WPP, in some hours of the day that the price was really low, the electricity price augments to keep the profit of the WPP to encourage the utilization of renewables.

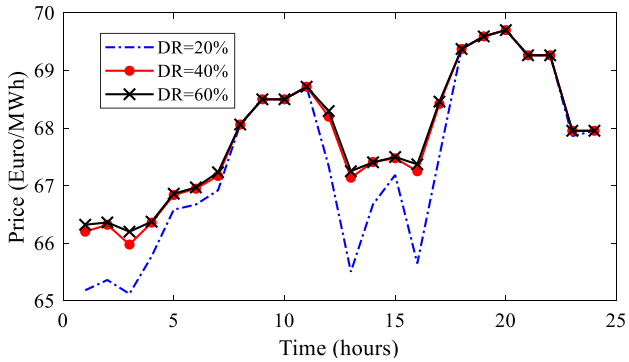

Fig. 7 Offering price of the WPP in β=1.

Power generation of DG units other than the WPP is given in Fig. 8 and Fig. 9. In order to avoid crowdedness, only generation in two DR participants (20% and 60%) is compared. As seen, DGs # 13 and # 16 as cheapest units commit always and DG# 25 generates power for a high number of hours compared with the other two units of #8 which is costly.

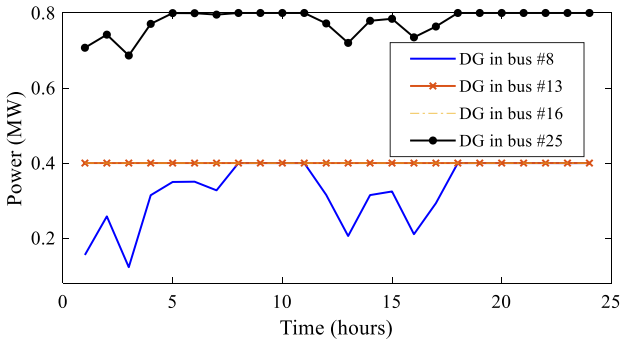

Fig. 8 Generation of DGs in DR=20% and β=1.

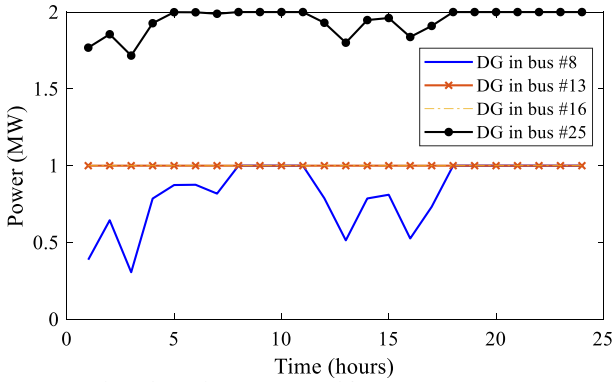

Fig. 9 Generation of DGs in DR=60% and β=1.

With comparing Fig. 8 and Fig. 9, it can be implied that with increasing DR percentage, the commitment drops due to reduction in requested power by the responsive loads. In this problem, the balancing market is considered to meet the load deviation which is presented in Fig. 10. In low DR participants, bidding too high energy by loads may result in high balancing energy exchanges to cover the energy mismatch.

With increasing DR participants, the wind generation outputs would be addressed more. So, the energy compensation in the balancing market reduces, although in some points the energy exchanges vary marginally.

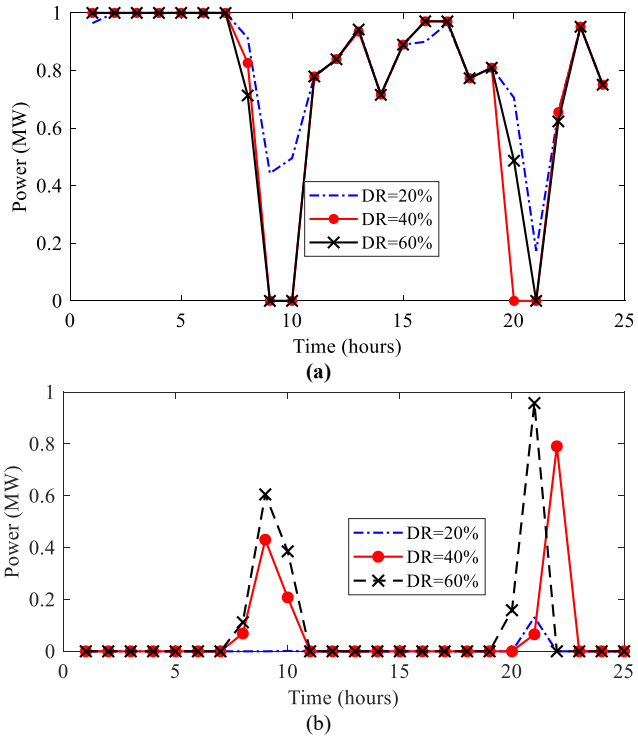

Fig. 10 Energy exchange in (a) down (b) up regulating market: in β=1 and in different DR values.

V. Conclusion

In this paper, a decision-making strategy of a WPP was investigated to find its optimal offering in DA market. In addition, energy deviation of that strategic WPP was also covered in regulating market. On the other side, the network operator responsive utilized responsive loads through a P2P trading floor to reduce the market power of the strategic WPP. The platform of this problem is modeled as a bi-level problem in which the price maker WPP is in the top level, while the network operator is in the lower level. The obtained problem is converted to a single level framework using mathematical tools. In addition to that, CVaR measurement is applied to the problem to hedge against uncertainty of problem. The proposed problem is verified in a case study with IEEE 33 bus test system. The obtained results illustrated that with utilizing demand side management, market power of the strategic WPP reduces and so, responsiveness of loads is a promising method towards a more competitive market. Furthermore, it is obtained that with increasing DR participants, the unit commitment reduces because of the mitigation in requested demand. In addition, with increasing DR, since the wind power is addressed, the amount of energy compensated in the balancing market is also reduced.

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