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Strategic Offering of a Price Maker Wind Power Producer in Distribution-Level Energy Markets in Presence of Flexible Prosumers

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ABSTRACT This paper presents an optimal bidding strategy for a strategic wind power producer (WPP) in a distribution-level energy market (DLEM). The behavior of the WPP is modelled through a bi-level stochastic optimization problem where the upper-level problem maximizes the profit of the WPP and the lower-level problem describes the clearing processes of the DLEM while considering network constraints. The bi-level problem is a stochastic mathematical program with equilibrium constraints (MPEC) that is formulated as a mixed-integer linear programming (MILP) problem. The main focus of this study is investigating prosumers' impact on the market power of the strategic WPP in a DLEM structure. In this model, the effect of flexible prosumers from the aspects of demand response (DR) participants and photovoltaic penetration level (PVPL) on the WPP's offering strategy is investigated. Moreover, the impact of bilateral contract on the market power of the strategic WPP and the cleared prices of the network is addressed. The proposed model is implemented in an IEEE 33-bus and numerical results illustrate how behavior of flexible prosumers and PVPL index affect the decision making of the strategic WPP when network constraints are considered. Numerical results show that by active participation of prosumers in DR programs, the reliance of DLEM on the strategic WPP reduces. Moreover, if the WPP participates in bilateral contracts, its offering to the DELM decreases, and as the result, the cleared prices augment indicating market power of the WPP.

INDEX TERMS Bi-level model, distribution-level energy market (DLEM), distribution network (DN), optimal offering strategy, wind power producer (WPP).

NOMENUCLATURE

PARAMETERS

Sets and indices

$(\cdot)_{t,\omega}$	At time t and in scenario ω.
l, n	Line number, bus number.
k	Index of DG unit cost segments.
Res	Denotes responsive loads.
$t \in T$	Index and set of time periods.
$G \in N_G$	Index and set of conventional generating units.
$WPP \in N_{WPP}$	Index and set of wind generation unit.
$PV \in N_{PV}$	Index and set of photovoltaic unit PV.
$D \in N_D$	Index and set of demand load D.
$l \in N_L$	Index and set of line l.
$s(l) = n$	Sending-end of line l.
$r(l) = n$	Receiving-end of line l.
$\underline{(\cdot)}, \overline{(\cdot)}$	Lower (upper) limit of parameter $(\cdot)$.
B_l	Susceptance of line l (p.u).
P^D	Demand of load D (MW).
P^G	Power of DG unit G (MW).
P^{WPP}	Power of WPP (MW).
P^{PV}	Power of photovoltaic system (MW).
$P^{WPP}_{t,\omega}$	Generated power by the WPP (MW)
$f_l^{\max}$	Transmission capacity of line l (MW).
$C^{up/dn}_{t,\omega}$	Up/down regulation market prices (€/MWh).

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C_t^{WPP}	Marginal cost of WPP (€/MWh).
C^G	Marginal cost of generation unit G (€/MWh).
$c_{p,t}^k$	Offered cost of block k of DR provided by prosumer p (€/MWh).
$P_{t,\omega}^{WPP}$	Total wind generation of WPP (MWh).
$P_{t,\omega}^{WPP,bil}$	The amount of wind power that the WPP contracted in bilateral contract (MWh).
$q_{p,t}^{k,\max}$	Maximum power of block k of prosumer p (MW).
$DR_{p,t}^{\max}$	Maximum power of prosumer p (MW).
π_ω	Probability of scenario ω.
$C_{n,t,\omega}$	LMP at bus n (€/MWh).
$DR_{p,t}$	Amount of power of prosumer p traded in the network (MW).
$CDRP_{p,t,\omega}$	Cost of DR related to prosumer p (€/MWh).
$P_{t,\omega}^{WPP,cl}$	Wind power cleared in the DA market for the WPP (MW).
$P_{t,\omega}^{WPP,of}$	Wind power offered to DA market by WPP (MW).
$P_{t,\omega}^G$	Power scheduled to be produced by generation unit G (MW).
$P_{t,\omega}^{PV}$	Power production of PV system (MW).
$P_{t,\omega}^{up/dn}$	Up/down regulation power (MW).
$\alpha_{W,t}$	Offering price of WPP (€/MWh).
$q_{p,t,\omega}^k$	Scheduled power of block k of prosumer p (MW).
$P_{t,\omega}^D$	Scheduled power to be consumed by demand D (MW).
$P_{t,\omega}^{D,Res}$	Required demand of responsive loads (MW)
$C_{t,\omega}^D$	Marginal utility of demand D (€/MWh).
θ_n	Voltage angle at bus n.
f_l	Power flowed from line l (MW).

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

The environmental concerns, the fossil fuel crisis, and also subsidies for wind power generation have significantly yielded to the development of wind energy in many electricity systems throughout the world [1]. By increasing wind power penetration in distribution networks (DN), due to the uncertain and un-dispatchable nature of that power, the participation of wind power producers (WPPs) in the short term electricity markets is a significant challenging problem [2]. Unlike the owners of conventional generators, a WPP has to take more careful strategies for selling energy in the day-ahead (DA) trading floor that is because of the stochastic nature of wind generation. On the other hand, findings of previous studies show that demand response (DR) programs are flexible and cost-effective options for controlling the stochastic nature of WPPs [3]. However, in demand side by growing the distributed energy resources (DERs) and rapid development of smart meters and communication technologies, many passive electrical consumers transfer into active prosumers [4]. Active prosumers play a significant role in the electricity markets and DN by managing their energy consumption and local production [5]. Although prosumers' flexibility with demand-side energy management (DSM) can bring economic benefits for prosumers and the DN operators (DNOs) [6], their random and intermittent natures can affect the optimal reactions of a WPP [7].

In previous works in the field of DSM, some researchers have investigated the influence of demand-side management on the optimal strategies of WPPs [8]–[12]. In [8], an optimum bidding strategy has been provided for the pairing of WPP and demand-side resources, in which the WPP used DR options to compensate benefit losses caused by wind power variabilities. Authors in [9] have developed a bi-level stochastic strategy for a WPP in DA and real-time (RT) markets, where optimal bidding of the WPP and its participation to supply DR aggregators are specified to obtain maximum profit. Also, a two-stage offering strategy has been reported in [10], in which WPP uses DR as a joint operational source. In the first stage, the WPP decides on DA offers and simultaneously determines the contribution of DR agreements and in the second stage correction actions made on the real-time market. In [11], a framework has been given to obtain optimal offering strategy for a hybrid generation unit including a WPP and DR resources in the electricity market. Moreover, a bi-level optimization model for offering strategy of WPP has been proposed in [12], in which the WPP can take part in both DA and balancing oligopoly markets as a price-maker to maximize its profit. In that model, the effect of DR on the WPP's decision making has been investigated under intraday DR exchange (IDRX) architecture. However, the studies in [8]–[12] only have paid attention to determine the optimal offering strategies of WPPs and did not investigate the market power of the WPP. Also, the mentioned works only considered the participation of responsive demands in DR program and the flexibility of end-use prosumers are not addressed.

During last years, throughout the world, there has been a substantial increase in the installed capacity of renewable resources such as wind production. A WPP with large-scale wind power integration can affect the electricity price and play strategically to set the price [13]. Market power of a strategic WPP can increase the level of market-clearing prices and lead to a loss of social welfare of end-users [14]. On the other side, DR actions can reduce energy generators' potential to exercise market power, since energy consumption is mitigated at high electricity prices; therefore, restricts the volume of power offered by strategic units [14] and [15]. In [15] the effective influence of demand shifting in reducing market power has been investigated by a multi-period equilibrium programming model of the non-ideal trading floor. However, the above-mentioned studies only have demonstrated the effect of DSM on the market power while the impact of flexibilities of prosumers on the market power of a WPP in a price-maker setting has not been studied.

B. SCOPE AND CONTRIBUTIONS

This paper attempts to investigate DSM considering prosumers' flexibility on the market power of a strategic WPP in a distribution-level energy market (DLEM). In this regard, a stochastic bi-level optimization model is developed, that in the first level the WPP, as a strategic producer aims to maximize the profit, and in the second level the DNO clears local market to minimize the operational cost of DN. Moreover, in the lower level, the flexible prosumers with photovoltaic (PV) systems participate in DR programs and trade energy with DLEM. To capture the related uncertainties, i.e., PV power generation, power of the WPP, bidding price and demand of prosumers as well as market prices, a scenario-based method is used in the proposed problem.

In the proposed model, local energy market clearing is done in a distribution local market as DLEM.

Although, DLEM is assumed to have similar structure to the wholesale market [16], [17], it faces more uncertainty rather than the wholesale market due to volatile local demand and greater influence of intermittent renewable generations in most cases. Moreover, with developing smart meters and communication technologies in demand side, passive consumers are changed into responsive prosumers. In such conditions, the prosumers can trade power with the system operator and regulate energy mismatch in real-time. In this regard, flexibility of prosumers can be used as one of the best solutions to control the uncertainty level of RESs generations in the transactive DLEM [18]. In this work, the main focus is on the potential of active prosumers for the energy mismatch in real-time market in the transactive DLEM. In this structure, the effect of prosumers participation in DR programs and their energy trade with system operator and regulate energy mismatch in real-time have been studied.

Moreover, in this study, the effect of demand-side flexibility and local renewable resources on the market power of the WPP and congestion alleviation in the distribution grid is carefully investigated. Therefore, the contributions of this study are listed as follow:

- A bi-level model is provided which is mathematically formulated through a stochastic programming approach. In the upper level, offering strategy of a price maker WPP considering prosumers actions under transactive energy framework to regulate energy mismatch in real-time is modelled. Also, in the lower level, the DNO conducts the local electricity market clearing considering the injected energy of the local prosumers such that to maximize the social welfare with considering technical limitations.
- A local electricity market is modelled from a strategic WPP's point of view as DLEM in which the effects of prosumers' participation in DR actions in transactive DLEM on the market power index (MPI) of strategic WPP and the social welfare of distribution network have been extensively investigated.
- The effect of active participation of prosumers in DELM from aspects of DR participants and PVPL index on the WPP's offering strategy and on the locational marginal price (LMP) and network congestion margin is studied. Furthermore, the effect of entering the strategic WPP in bilateral contracts and consequently reducing its offering power to DA market on the cleared price of the network is addressed.

C. PAPER ORGANIZATION

The remaining of the paper is organized as follows. Section 2 explains the proposed strategic offering of WPPs and the modelling assumptions. Section 3 presents the mathematical model of the imperfect electricity market, and Section 4 gives a case study with numerical results. Finally, the conclusion and future work is given in Section 5.

II. PROBLEM DESCRIPTION AND SYSTEM MODELING

A. PROBLEM DESCRIPTION

This work proposed a decision making problem to specify optimum offering strategy of a strategic WPP in DLEM. In this model, a short term local electricity market including DA and RT markets are considered as DLEM, which is similar to the model of European pool-based electricity systems [10]. DLEM is used in a typical DN consisting of a strategic WPP, several distributed generation (DG) units and different groups of active prosumers. The WPP is supposed to be a price-taker in the RT market and has market power in the DA trading floor. The WPP suggests its offering quantities and DA offer prices for each hour of the next day. Also, the prosumers declare the amount of energy that they will buy or sell in the DLEM. In this structure, two groups of prosumers are considered in different locations of the network as smart building and smart industrial centres. Each group of industrial centres are equipped with PV panels and can participate in DLEM and trade energy with DN. Also, all group of prosumers has a known load profile that must be satisfied by DN and local PV generations in industrial centres.

In the proposed framework, the WPP and conventional DGs submit their generation offers and each group of prosumers submit its bid independently. The DNO, as a responsible agent for participating in DLEM, gathers the offers of the WPP and DGs, and bids of prosumers (e.g., DR capability and initial hourly demand) and then determines optimal market prices based on network constraints and DLEM regulations.

In addition, the WPP may be willing to supply local loads through bilateral contracts. In this regard, the proposed model is developed as a two-stage bi-level stochastic optimization problem, where in the upper level, the profit of the WPP is maximized and in the lower level DLEM is cleared by DNO to maximize the social welfare. The obtained bilevel problem is recasted to a single level one using Karush-Kuhn-Tucker (KKT) optimality conditions. Moreover, the non-linearities are transformed to the linear form using complementary constraints. Also, the bilateral contracts as long term power exchange commitments are incorporated in the problem modelling. FIGURE 1 illustrates the overview of the proposed

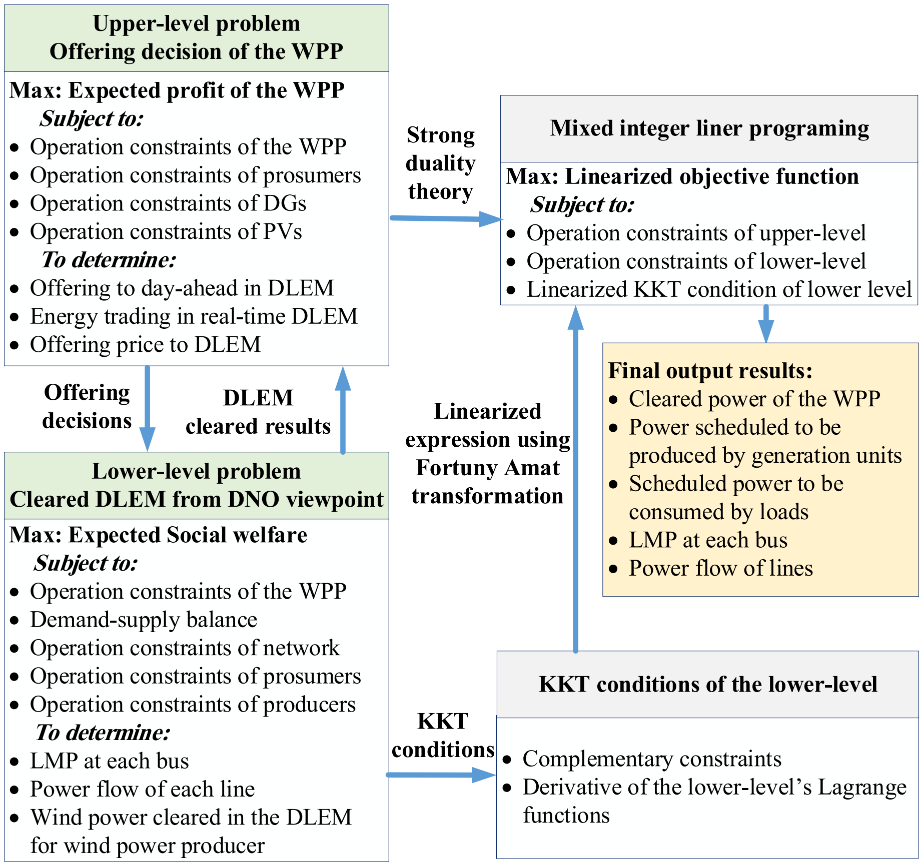

FIGURE 1. Overview of the proposed framework.

framework. In this stochastic model, the variabilities of the WPP, PV generation, demand and electricity prices are taken into account.

In this model, there exists a network controller and a market controller. The DNO who plays the role of network controller is responsible for scheduling the available energy resources, loads with considering technical constraints. The market controller is responsible for dealing with energy transaction to keep balance for energy cost. In such condition, the WPP and other DGs and also loads submits their energy offers and bids. When market is cleared, they will be informed about the energy is sold or purchased from.

For the clarification, the main assumptions considered in this problem are listed below:

- DNO is the responsible agent for participating in DLEM and it clears the market based on DN constraints.
- The WPP behaves strategically in DA market while it can compensate its production deviation in the regulating market [19].
- The price and quantity bids submitted by the loads across periods is predicted through scenarios.
- The WPP can submit its generation to the grid or it can supply local loads through bilateral contracts.
- DG units other than the WPP are assumed to behave fully competitive in the market and submit their marginal costs.
- Each DG unit is located at its corresponding bus and is paid at the LMP of its bus.

B. MODELING OF PROSUMERS PARTICIPANTS IN DR PROGRAMS

To develop a market-based DR model for the prosumers' responses in DLEM, it is assumed that the prosumers bid their load mitigation the same as DGs that offer their power production. In this base, DR cost is the product of the DR price and DR bidding quantity. Each group of prosumers p provides a price-quantity offer that presents the relation between load reduction and DR service prices at each time slot. Mathematical model of prosumers price-quantity is given in (1)-(4), [20].

$$P_{t,\omega}^{D,\mathrm{Res}} = \sum_{k=1}^{NQ_p} q_{p,t,\omega}^{k} \tag{1}$$

$$CDRP_{p,t,\omega} = \sum_{k=1}^{NQ_p} c_{p,t,\omega}^{k} q_{p,t,\omega}^{k} \tag{2}$$

$$q_{p,t,\omega}^{k} \le q_{p,t}^{k,\max} \tag{3}$$

$$P_{t,\omega}^{D,\mathrm{Res}} \le DR_{p,t}^{\max} \tag{4}$$

Constraints (1)-(4) describe DR services provided by prosumers to support the DSO operation. NQ_P denotes the number of bidding blocks of DR provided by prosumer p. Constraints (1) and (2) give DR quantity and DR cost purchased from a group of prosumer p, respectively. Also, constraints (3) and (4) provide the limits of quantity of DR services and DR capacity that is provided by the group of prosumer p, respectively.

C. UNCERTAINTIES CHARACTERIZATION

In the proposed stochastic model, a major set of uncertainties including uncertainty of WPP's power production, PV generation, price and quantity bidding of loads and regulating market prices are considered. These uncertain parameters are forecasted in advance at each hour that their forecast errors are modelled by proper probability distribution functions (PDFs) [21]. For each of the stochastic parameters, a set of scenarios is defined according to the related PDF. Then, the scenarios tree is built and the sets of scenarios are combined and their corresponding probabilities are also obtained. By combining all of the scenarios, a large set of scenarios is obtained, that would lead to computational intractabilities. So, scenario reduction should be used to remove scenarios with very low probability and collect the same scenarios in terms of probability metrics [22]. The output of the scenario reduction algorithms is a set of scenarios of the smaller sizes with their corresponding probabilities [23].

In this study, each uncertain parameter is modelled with 100 scenarios. Then, these original scenarios are combined and mitigated to 81 scenarios using *K-means* algorithm [24] for computational tractability. *K-means* algorithm aims at minimizing the measure between the centroid of the cluster and the given observation iteratively appending an observation to any cluster and terminate when the lowest distance measure is achieved. Common distance measures (the same as the one used in this study) include the Euclidean distance that corresponds to the shortest geometric distance between two points. Finally, a finite set of possible scenarios are combined to build the scenario tree.

The verification of the correctness of the algorithms and systems will be conducted using the methods and tools described in [25] and [26].

III. MATHEMATICAL MODELING OF IMPERFECT ELECTRICITY MARKET

The problem of the optimal offering of the strategic WPP with market power is modeled via a stochastic bi-level framework as below:

A. BI-LEVEL MODEL FORMULATION

The obtained bi-level model is recast as a single level MPEC by replacing the lower level by its KKT optimality constraints to derive the strategic WPP's optimal strategy when participates in DLEM. In the upper-level problem, the WPP maximizes its expected profit as follows:

$$Max \sum_{\omega\in\Omega} \pi_\omega \sum_{t\in T} \begin{bmatrix} P^{WPP,cl}_{t,\omega} C_{n,t,\omega} - P^{WPP}_{t,\omega} C^{WPP}_{t} \\ +P^{dn}_{t,\omega} C^{dn}_{t,\omega} - P^{up}_{t,\omega} C^{up}_{t,\omega} \end{bmatrix} \quad (5)$$

The objective function (5) is also subject to the power balance as given in (6):

$$P^{WPP}_{t,\omega} - P^{dn}_{t,\omega} + P^{up}_{t,\omega} = P^{WPP,cl}_{t,\omega} \quad (6)$$

where the energy deviations originated from wind power forecasting is settled in the regulation market. Moreover, the produced wind power is restricted within its capacity.

$$P^{WPP}_{t,\omega} \leq \bar{P}^{WPP} \quad (7)$$

The upper-level problem is subject to the lower level one from the viewpoint of the DNO representing the market-clearing such that to maximize the social welfare. Therefore, the lower level problem can be formulated as follow:

$$Min \sum_{\omega\in\Omega} \pi_\omega \sum_{t\in T} \left[P^{G}_{t,\omega} C_G + \alpha_{WPP,t} P^{WPP,cl}_{t,\omega} - P^{D}_{t,\omega} C^{D}_{t,\omega} \right] \quad (8)$$

The lower level problem would be subject to power balance constraints. For the buses including each of the generation units, WPP and PV generation, the power balance includes:

$$\begin{aligned} &\sum_{G\in N_G} P^{G}_{t,\omega} + \sum_{WPP\in N_{WPP}} P^{WPP,cl}_{t,\omega} + \sum_{PV\in N_{PV}} P^{PV}_{t,\omega} \\ &\quad - \sum_{D\in N_D} P^{D}_{t,\omega} - \sum_{D\in N_{D,\mathrm{Res}}} P^{D,\mathrm{Res}}_{t,\omega} \\ &\quad - \sum_{l|s(l)=n} f_l + \sum_{l|r(l)=n} f_l = 0 : C_{n,t,\omega} \end{aligned} \quad (9)$$

Also, the power flow from each line is given as:

$$f_l = B_l(\theta_{s(l)} - \theta_{r(l)}) : \beta_l \quad (10)$$

that is restricted with the following limitation:

$$-f^{\max}_l \leq f_l \leq f^{\max}_l : \beta^{\min}_l, \beta^{\max}_l \quad (11)$$

Also, the limit of load demand, as well as PV and DGs productions, is as follow:

$$0 \leq P^{D}_{t,\omega} \leq \bar{P}^{D} : \varepsilon^{\min}_D, \varepsilon^{\max}_D \quad (12)$$

$$0 \leq P^{PV}_{t,\omega} \leq \bar{P}^{PV} : \varepsilon^{\min}_{PV}, \varepsilon^{\max}_{PV} \quad (13)$$

$$0 \leq P^{G}_{t,\omega} \leq \bar{P}^{G} : \varepsilon^{\min}_G, \varepsilon^{\max}_G \quad (14)$$

The cleared power of WPP is restricted with the power offered by the WPP to the DNO, as presented in (14).

$$0 \leq P^{WPP,cl}_{t,\omega} \leq P^{WPP,of}_{t,\omega} : \varepsilon^{\min}_W, \varepsilon^{\max}_W \quad (15)$$

The voltage angle of each node is within its limitation and the voltage angle of reference node is fixed to zero as given in the two following constraints.

$$-\pi \leq \theta_n \leq \pi : \mu^{\min}_n, \quad \mu^{\max}_n, \ \forall n\backslash n : ref \quad (16)$$

$$\theta_n = 0 : \gamma_n \quad n : ref \quad (17)$$

In the above expressions, the Lagrangian multipliers considered as dual variables are given after colon.

B. MPEC MODELING OF THE PROPOSED BI-LEVEL PROBLEM

According to the continuity and convexity of the lower level problem, it would be substituted with KKT optimality conditions [27]. For the bi-level problem converted to its MPEC, a set of variables consists of the variables of both upper and lower levels, and a set of Lagrangian multipliers corresponding to the lower level limits given by (18).

$$\left\{ \begin{array}{l} C_{n,t,\omega}, \beta_l, \beta_l^{\min}, \beta_l^{\max}, \varepsilon_D^{\min}, \varepsilon_D^{\max}, \varepsilon_{PV}^{\min}, \varepsilon_{PV}^{\max}, \\ \varepsilon_G^{\min}, \varepsilon_G^{\max}, \varepsilon_{WPP}^{\min}, \varepsilon_{WPP}^{\max}, \mu_n^{\min}, \mu_n^{\max}, \gamma_n \end{array} \right\} \tag{18}$$

The KKT optimality conditions of the lower level problem can be given as below:

$$C^G - C_{n,t,\omega} - \varepsilon_G^{\min} + \varepsilon_G^{\max} = 0 \tag{19}$$

$$\alpha_{WPP,t} - C_{n,t,\omega} - \varepsilon_{WPP}^{\min} + \varepsilon_{WPP}^{\max} = 0 \tag{20}$$

$$C_{t,\omega}^D - C_{n,t,\omega} - \varepsilon_D^{\min} + \varepsilon_D^{\max} = 0 \tag{21}$$

$$C_{n(s),t,\omega} - C_{n(r),t,\omega} - \beta_l - \beta_l^{\min} + \beta_l^{\max} = 0 \tag{22}$$

$$\sum_{l|s(l)=n} B_l \beta_l - \sum_{l|r(l)=n} B_l \beta_l - \mu_n^{\min} + \mu_n^{\max} = 0, \quad \forall n \backslash n : ref \tag{23}$$

$$\sum_{l|s(l)=n} B_l \beta_l - \sum_{l|r(l)=n} B_l \beta_l - \gamma_n = 0, \quad n : ref \tag{24}$$

$$0 \le \beta_l^{\max} \perp f_l^{\max} - f_l \ge 0 \tag{25}$$

$$0 \le \beta_k^{\min} \perp f_l + f_l^{\max} \ge 0 \tag{26}$$

$$0 \le \varepsilon_D^{\max} \perp \bar{P}^D - P_{t,\omega}^D \ge 0 \tag{27}$$

$$0 \le \varepsilon_{PV}^{\max} \perp \bar{P}^{PV} - P_{t,\omega}^{PV} \ge 0 \tag{28}$$

$$0 \le \varepsilon_D^{\min} \perp P_{t,\omega}^D \ge 0 \tag{29}$$

$$0 \le \varepsilon_{PV}^{\min} \perp P_{t,\omega}^{PV} \ge 0 \tag{30}$$

$$0 \le \varepsilon_G^{\min} \perp P_{t,\omega}^G \ge 0 \tag{31}$$

$$0 \le \varepsilon_G^{\max} \perp \bar{P}^G - P_{t,\omega}^G \ge 0 \tag{32}$$

$$0 \le \varepsilon_W^{\max} \perp P_{t,\omega}^{WPP,of} - P_{t,\omega}^{W,cl} \ge 0 \tag{33}$$

$$0 \le \varepsilon_{WPP}^{\min} \perp P_{t,\omega}^{WPP,cl} \ge 0 \tag{34}$$

$$0 \le \mu_n^{\max} \perp (\pi - \theta_n) \ge 0, \quad \forall n \backslash n : ref \tag{35}$$

$$0 \le \mu_n^{\min} \perp (\pi + \theta_n) \ge 0, \quad \forall n \backslash n : ref \tag{36}$$

C. MILP MODEL OF THE STRATEGIC OFFERING OF THE WPP

The MPEC model of the strategic offering of the WPP includes the nonlinear production of $P_{t,\omega}^{WPP,cl} C_{n,t,\omega}$. Based on the convexity of the problem, strong duality theory and some mathematical relations are used and the linear form of the bilinear expression is obtained as below:

$$\begin{aligned} P_{t,\omega}^{WPP,cl} C_{n,t,\omega} = & \sum_{D \in N_D} P_{t,\omega}^D C_{t,\omega}^D - \sum_{G \in N_G} P_{t,\omega}^G C^G \\ & - \sum_{l \in N_L} f_l^{\max} (\beta_l^{\min} + \beta_l^{\max}) \\ & \times \sum_{G \in N_G} (-\varepsilon_G^{\max} \bar{P}^G - \varepsilon_D^{\max} \bar{P}^D) \\ & - \sum_n \pi (\mu_n^{\min} + \mu_n^{\max}) \\ & - \sum_{WPP \in N_{WPP}} P_{t,\omega}^P C_{WPP,t}^P \\ & + P_{t,\omega}^{dn} C_{t,\omega}^{dn} - P_{t,\omega}^{up} C_{t,\omega}^{up} \end{aligned} \tag{37}$$

The MPEC problem includes other nonlinear terms due to complementarity conditions expressed with the production of primal and dual variables shown with the sign ⊥. These relations can be replaced with their corresponding linear expression using the approach given in [28].

D. MARKET POWER INDEX

In order to quantify the market power of the WPP, an index is defined here. Based on this index, the offering price that is cleared in DA market is compared with a base case. This expresses the average increment of market prices driven by the exercise of market power. Here, the base case is considered as the case in DR = 0% and PVPL = 0% that other cases would be compared with it.

$$MPI = \frac{\hat{C}_n^{base} - \hat{C}_n}{\hat{C}_n^{base}} \tag{38}$$

where, $\hat{C}_n^{base}$ denotes the average of cleared price in base case and $\hat{C}_n$ is average of the cleared price in other case.

IV. CASE STUDY AND NUMERICAL RESULTS

A. CASE STUDY

The proposed model is tested on a modified IEEE 33-bus distribution system presented in FIGURE 2. As observed, this system consists of one strategic WPP in bus 14 with the capacity of 10MW, conventional generators DG1-DG3 in buses 8, 13, 15 with the maximum capacity of 1MW and DG4 unit in bus 25 with the maximum capacity of 2MW. It is considered that the WPP can inject its wind generation to the grid or it can enter bilateral contracts and supply its local loads. Marginal costs of the four DG units are 61.3, 61.5, 61.2 and 61.8 €/MWh extracted from [27] Moreover, five industrial loads P1-P5 as flexible prosumers in buses 8, 13, 14, 15 and 25, that are equipped with PV panels, and some responsive loads. Also, the cost of wind power production is supposed to be null. The hourly forecasted power of the WPP and PV of each group of prosumers is given in

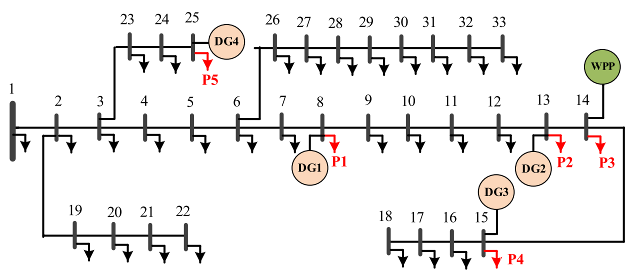

FIGURE 2. Single line diagram of the modified IEEE 33 bus [29].

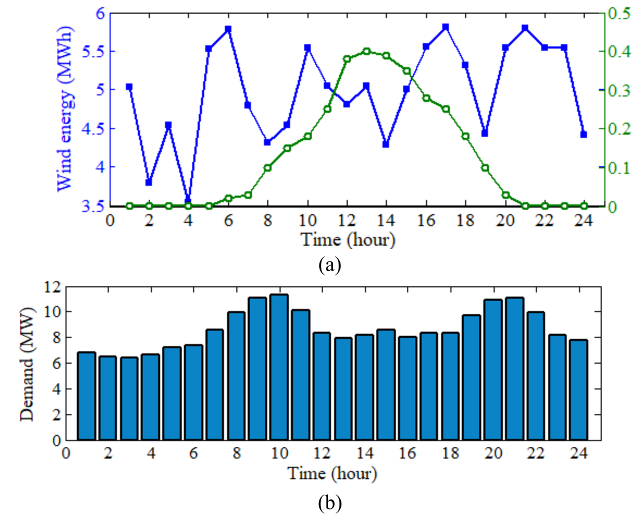

FIGURE 3. **(a) Forecasted output power of WPP and output power of PV generated by each prosumer (b) Forecasted load demand.**

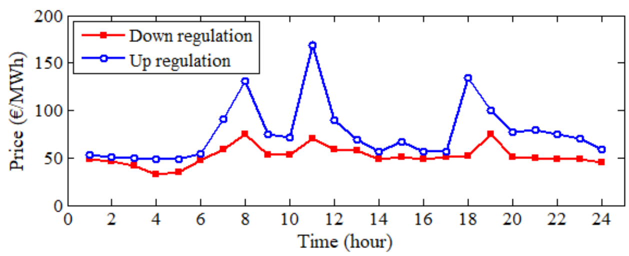

FIGURE 4. **Regulating market prices.**

FIGURE 3 (a). Also, the load profile of total demand of the network is displayed in FIGURE 3 (b), [19]. The excess or lack of energy can also be compensated in the up-and down-regulating market with the prices shown in FIGURE 4.

The optimization problem is investigated for different operation conditions of PV penetration level (PVPL) and DR participant. In the simulation process, at first, the MCS method can be implemented to generate scenarios for each stochastic parameter which would then be reduced to 81 final scenarios by implementing K-means method [24]. Hence, the final scenario set is submitted to the optimization problems for maximizing the expected profit of DNO. All numerical experiments have been executed on a computer with 4 GB of RAM and Intel Corei7@2.60GHz processor with GAMS software and CPLEX solver [30]. The computation times in different cases are less than 8 minutes that shows the practical aspect of the proposed strategy.

B. NUMERICAL RESULTS

The offered and cleared wind power of the strategic WPP in DR = 50% and PVPL = 50% is shown in FIGURE 5. PVPL is defined as the ratio of total installed capacity of PV production to the maximum required load. It is seen that the offered wind power changes during the day that is due to wind generation variability. Regarding the market power of the WPP, its offered power is equal with the cleared wind power. Also, the excess or lack of generation would be settled in the regulating market. Also, seen that the WPP offers the wind power production, since it seeks the achievements from the network.

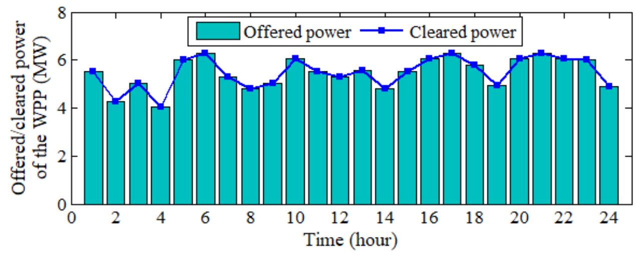

FIGURE 5. **Hourly offered and cleared power of the WPP.**

FIGURE 6 illustrates the offering price of the WPP in different PVPL and DR participants. FIGURE 6 (a) shows that in a fixed DR percentage, with increasing PVPL, the offering price by the WPP reduces in some hours of time horizon. Since by increasing PV power, green prosumers behave sustainably and try to supply their loads from local PV solar. Therefore, the reliance of the DNO on the WPP power may reduce totally. That is reasonable because the prosumers can absorb from or feed-in energy to the grid.

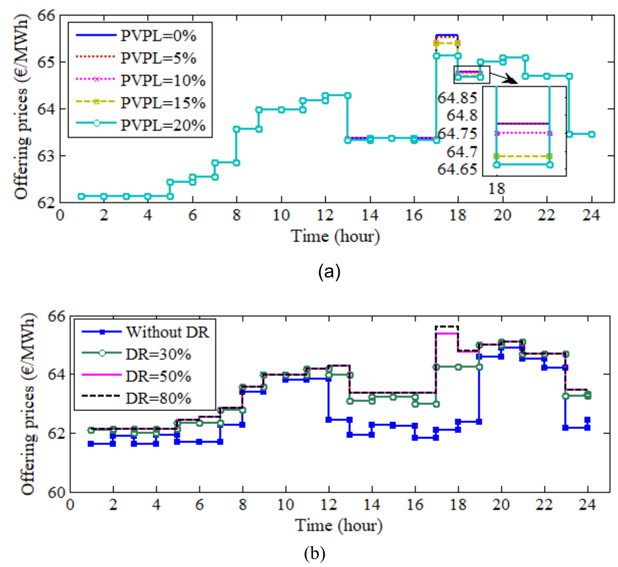

FIGURE 6. **Offering prices of the WPP, (a) in different PVPL and DR = 50%, (b) in different DR and PVPL = 50%.**

Moreover, FIGURE 6 (b) illustrates the offering price of the WPP for different DR participants and PVPL = 50%. As observed, with increasing DR participants, since the required demand of the network would be reduced during peak periods and it augments in off-peak hours, the price offered by the WPP increases specifically during off-peak and middle hours of the day. That is because, the WPP has market

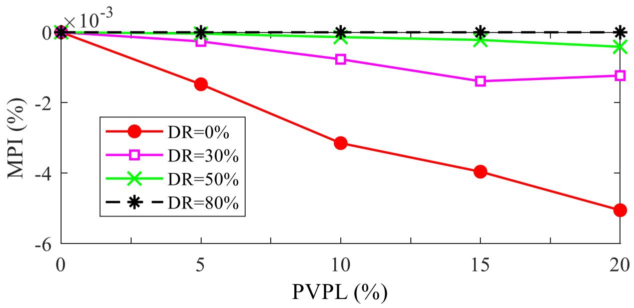

FIGURE 7. MPI in different DR and PVPL percentages.

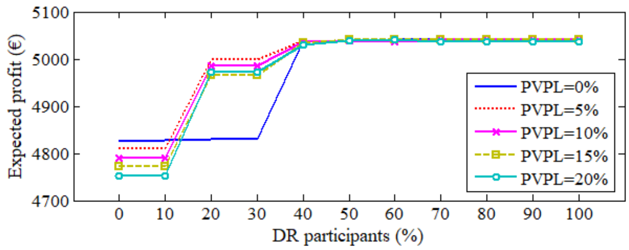

FIGURE 8. Expected profit of the WPP versus DR participants and PVPL.

power, so it augments the prices during the hours with high loads.

To better show the market power of the WPP, MPI index is quantified in different DR and PVPL percentages as shown in FIGURE 7 As seen, in constant DR participants, with increasing PVPL, since the prosumers can inject their local energy to the grid, the customers has more flexibility to choose their energy resource. Therefore, the market power of the WPP reduces. While, in a constant PVPL and with increasing DR participants, MPI augments that implies the increment of market power of the WPP during the hours with higher load (i.e., the hours with load shifting). Such increment of MPI represents the market power exercised by the strategic WPP. It can be deduced that demand flattening and PV penetration can affect the extent of market power exercised by the strategic WPP contradictory. Meaning that with increasing PV generation, the market power of the WPP reduces, while the opposite occurs when applying for DR programs.

FIGURE 8 provides the expected profit of the strategic WPP in different DR participants and PVPLs. Be noted that the results given in FIGURE 8 are in accordance with those shown in FIGURE 6. As seen from FIGURE 8, by increasing PVPL, the expected profit of the WPP reduces. In fact, by promoting local energy utilizations, the dependency of the prosumers on the main grid reduces. This guarantees energy efficiency and benefits for both prosumers and DNO.

In fact, the prosumers can supply their load and feed in their surplus energy to the distribution network. Also, the DNO can supply the required demand with cheaper resources. So, the WPP offers lower prices to the main grid to attract the DNO to purchase wind production. Therefore, it is rational that with increasing PVPL penetration level and with reducing the offering price of the WPP, its expected profit decreases. However, the low decrement of the profit is due to lower price reduction that is driven by the exercise of the WPP market power. Moreover, by increasing DR participants, the expected profit of the WPP increases. After implementing DR programs, loads are shifted to other periods where there exists wind power availability. Also, by increasing DR, the offering price of the WPP augments as seen in FIGURE 6. Therefore, based on the market power exercised by the WPP to supply a high volume of network demand, it augments its prices and consequently, it achieves higher expected profit as more loads become price responsive.

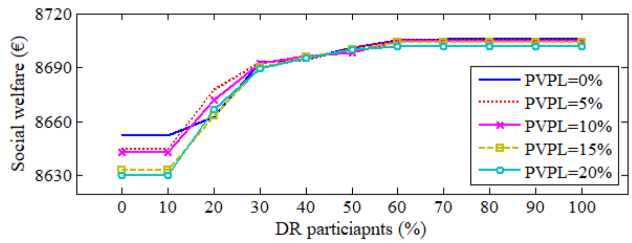

FIGURE 9. Social welfare versus DR participants in different PVPL.

FIGURE 9 illustrates social welfare in different values of DR participants and PVPLs. As seen, as more loads become responsive, social welfare augments which can be justified by the quantification of demand utility. In other words, implementing DR programs enables prosumers to keep their economic excess against the strategic behavior of producers. Furthermore, by increasing PVPL, social welfare declines. That is because the energy arbitrage between prosumers and the distribution network reduces and the on-site consumption of local renewable resources augments.

Total demand supplied by conventional DG units in different values of DR in different PVPL is shown in FIGURE 10. In higher DR participants, the load profile would be reshaped and a part of demand in peak period is shifted to the off-peak period. In such condition, cheaper DG units commit to supply loads in off-peaks and as a result, the total generation of DG units increases. In contrast to DR, by increasing PVPL and providing more demand by local PVs, the amount of net demand declines and so the total power supplied by DGs decreases.

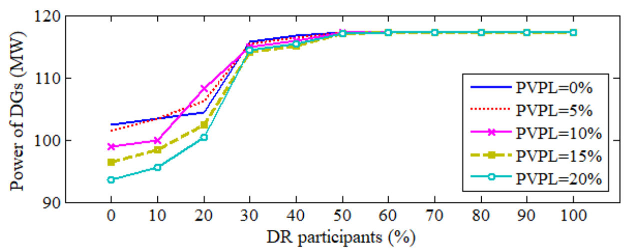

FIGURE 10. The total power supplied by DGs in different PVPL.

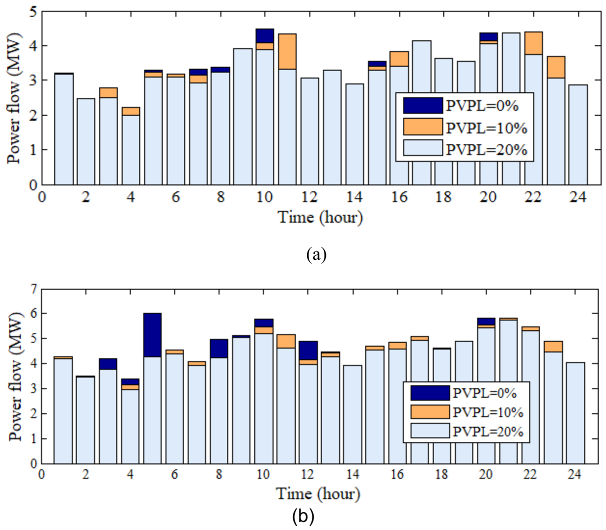

FIGURE 11. **Lines congestion status in DR = 50% and different PVPL, (a) Line 7 and (b) Line 13.**

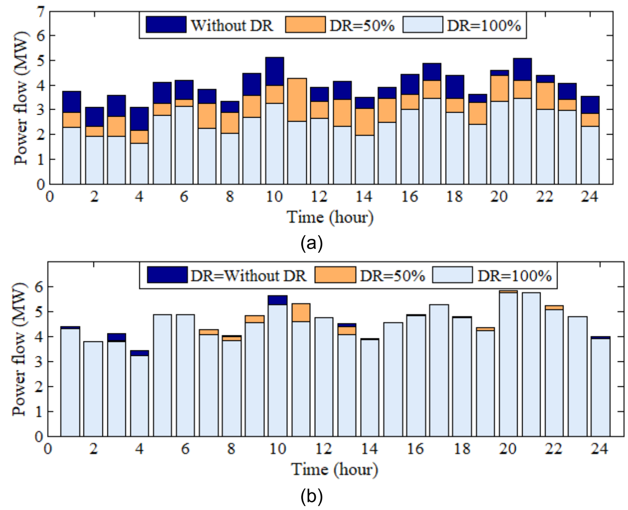

FIGURE 12. **Congestion status in PVPL = 50% and different DR participants, (a) Line 7 and (b) Line 13.**

For more investigation, the network congestion, load flow of two heavy lines, i.e. lines 7 (between bus 7 and bus 8) and line 13 (between bus 13 and bus 14) is investigated in different conditions. FIGURE 11 shows the average congestion values of two mentioned lines for DR = 50% and in three PVPLs. In generally line congestion occurs during peak periods that the branch is also overloaded. However, for the running time that PV power is generated, the line congestion reduces with increasing PVPL.

In fact, the loads are met by local PVs and consequently, power flow of the line declines. Furthermore, with increasing PVPL, line loading limit violations is prevented and the margin for load ability of the line augments. Therefore, although by increasing PVPL the line congestion is reduced, yet the line is congested. Consequently, by installing more PV units, the margin up to the power limit augments.

To study the effect of DR actions on the network congestion, the congestion circumstance of lines 7 and 13 in different DR in PVPL = 50% is shown in FIGURE 12. As seen, with increasing DR participants, lines congestion reduces, that is due to load decrement in peak periods after implementing DR programs. Therefore, the same as PVPL, the line congestion margin augments when DR participant increases.

FIGURE 13 illustrates the cleared price in both cases without and with a bilateral contract. The case without bilateral contract denotes that the WPP only injects its total generation (100%) to the grid. The case with bilateral contract implies that the WPP enters a bilateral contract and should supply local loads. Based on the amount of energy it signed in bilateral contract, it is considered that about 25%, 50% and 75% of remained wind generation is injected into the grid. In such conditions, different prices are obtained during the day. As seen, the cleared prices increase, as the WPP curtails its power injection to the grid. This interferes that when an electricity market owns large share of strategic units, these

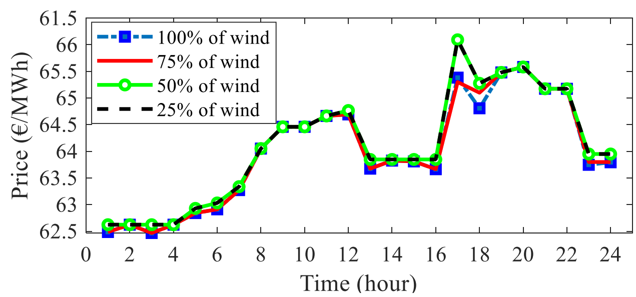

FIGURE 13. **Cleared price at bus 14 in different wind generation of WPP.**

strategic units can influence the electricity prices. In this case, if the strategic unit does not inject all of its generation into the grid, the cleared price augments.

V. CONCLUSION AND FUTURE WORK

In this paper, a bi-level stochastic framework was presented for determining the optimal strategy of a WPP as a price-maker in DLEM. Uncertainties of loads, renewables and electricity prices, are addressed. By applying the proposed model to IEEE 33-bus test system, several quantitative analyses are provided to analyse the influence of DR flexibility and promotion of local renewable resources on the strategic behaviour of the WPP. To this end, it can be implied that demand flattening and PV penetration can affect the extension of market power exercised by the strategic WPP on the contrary way. So, by active participation of prosumers, the reliance of DLEM on the strategic WPP reduces. Numerical results pointed that with increasing PVPL and DR participants, line congestion reduces due to supplying loads locally and reduction of loads and as the result, power flow of the line declines. Therefore, with increasing PVPL and DR, the margin to the power limit augments that leads to the responsive prosumers to be more flexible and to promote local renewable energy utilization for sustainable realizations. Also, it is concluded that if an electricity market owns large share of strategic units, these strategic units can influence the electricity prices. In this case, if the strategic unit does not inject all of its generation into the grid, the cleared price augments.

In future work, the proposed model will be developed and the impact of peer-to-peer trading floor between the large-scale aggregation of prosumers will be investigated on the market power of strategic producers in the DLEM.

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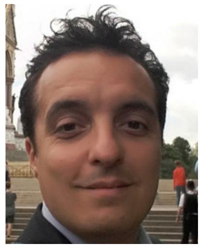

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