RESEARCH ARTICLE

Investigating the Impact of External Demand Response Flexibility on the Market Power of Strategic Virtual Power Plant

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ABSTRACT In this paper, a decision-making framework is proposed for a virtual power plant (VPP) to participate in day-ahead (DA) and regulating market (RM) considering internal demand response (IDR) flexibility. In the proposed model, a DR exchange market (DRXM) is also introduced to cover deviations of uncertain resources and decrease VPP's imbalance penalties in the RM. The VPP can optimize its procurement expenditures by providing DR services from both IDR providers and DRXM. A market inefficiency index (MII) is defined to analyze the effect of trading energy in the DRXM on the market power of the VPP. The proposed model is formulated as a bi-level problem, in which at the upper level, the VPP maximizes its profit while at the lower level, the distribution system operator (DSO) strives to clear both DA and RM markets to maximize social welfare. The proposed problem is nonlinear and converted into a linear single-level problem through Karush-Kuhn-Tucker (KKT) optimality conditions and duality theory. The simulation results show that in high external demand response (EDR) participants, the expected profit of the VPP augments about 3% which is a substantial value for the one-day scheduling horizon. Furthermore, by providing EDR services, MII reduces which implies the EDRs preserve their economic surplus.

INDEX TERMS Demand response (DR), decision-making problem, market power, regulating market (RM), virtual power plant (VPP).

NOMENUCLATURE

PARAMETERS

Sets and Indices

$(\bullet)_{t,\omega}$	At time t and in scenario ω.
$(\overline{\bullet})$	Maximum value of parameter $(\bullet)$.
k	Line number.
$\omega \in \Omega$	Set of scenarios.
n	Bus number.
$p \in N_p$	Set of EDR providers.
$t \in T$	Set of time.
$G \in N_G$	Set of generating units.

$V \in N_V$	Set of virtual power plant.
$D \in N_D$	Set for load groups.
$s(k), (r(k))$	Sending (receiving) bus of line k.

Parameters:

B_k	Susceptance of line k (per unit).
π_ω	Probability of scenario ω.
$\psi_1 \psi_2$	Parameter multiplied to obtain augment/reduction price.
$\lambda_{t,\omega}^{IDR}$	Offering price to internal loads (€/MWh).
$\lambda_{t,\omega}^{aug/red}$	Offering price in DR exchange market for upward (downward) DR services (€/MWh).

$P_{t,\omega}^{P}$	Predicted power of wind producer (MW).
$\bar{P}_{t,\omega}^{EDR,aug}$	Maximum amount of power provided by EDR providers (MW).
$\bar{P}_D$	Maximum power of demand loads (MW).
$\bar{P}_G$	Maximum power of generating units (MW).
$q_p^{aug/red}$	Shedding or increasing amount of load (MW).
$f_l^{\max}$	Maximum power flow of each line (MW).
$\lambda_{t,\omega}^{dn}$	Down regulating market price (€/MWh).
$\lambda_{t,\omega}^{up}$	Up regulating market price (€/MWh).
λ^{G}	Marginal cost of generating unit (€/MWh).
$\lambda_{t,\omega}^{D}$	Marginal utility of demand D (€/MWh).

Variables:

IDR/EDR	Internal/external DR.
DA/RM	Day ahead/regulating market.
$Cost^{G/VPP}$	Cost the DSO should pay to DG units/VPP.
$Income^{D}$	The revenue the DSO receives from the loads.
Pen	The penalty the VPP confronts in RM.
Rev	Revenue obtained from selling energy.
SW	The value of social welfare.
$\lambda_{n,t,\omega}$	Locational marginal price at bus n (€/MWh).
$P_{p,t,\omega}^{aug/red}$	Upward/downward DR services (MW).
$P_{t,\omega}^{DA}$	Cleared power of the VPP in the DA market (MW).
$P_{t,\omega}^{EDR/IDR}$	Supplied power of EDR/IDR resources by the VPP (MW).
$P_{t,\omega}^{G}$	Produced active power by dispatchable DG units (MW).
$P_{t,\omega}^{up/dn}$	Compensated power in up/down regulating market (MW).
α_t	Offering price by the VPP (€/MWh).
$P_{t,\omega}^{D}$	Active power of loads (MW).
$f_{l,t,\omega}$	Active power flow from each line (MW).
M_k	Transmission margin of line k (MW).

I. INTRODUCTION

Following strong economic support and social policy, the number of renewable generators (RGs) such as wind turbines and solar plants has increased in many countries in the past few years [1]. Although RGs bring more efficiency, their stochastic nature poses many challenges to the operation of the power systems. Moreover, RGs and also most of the non-RGs such as micro-turbines and fuel cells are usually distributed all around the network and cannot participate in the wholesale market, individually. To address the mentioned challenges, the implication of a virtual power plant (VPP) is suggested to integrate distributed generation units (DGs) as a unique entity for participation in the electricity market or for the provision of system support services [2].

Although a VPP enables control and optimization of energy generation, unfortunately when it has a high penetration of RGs, it may need an energy storage system (ESS) to reduce RG' uncertainties [3], [4], which results in high investment costs. In fact, without ESS, VPP's decision-making confronts risk due to forecasting error of RG' output in real-time operation. Fortunately, by developing smart meters and communication technologies in modern power systems, VPPs can use demand response (DR) flexibility as one of the best solutions to control the uncertainty and cover RG' deviations. In the smart environment, DR flexibility is known as one of the most effective solutions to lessen provision costs and flatten locational marginal prices (LMP) [5], [6]. Utilizing DR services can obtain various targets such as minimizing the operating costs, controlling the risk of participation in the market, reducing market price spikes, and compensating for RG intermittencies [7], [8].

Most researchers have proposed different offering strategy models for VPPs, in which flexible DR resources are used to decrease VPP's imbalance penalties in the real-time market [9]. In [10], a two-stage risk-constrained stochastic model has been suggested for offering strategy of a VPP taking part in the day-ahead (DA), regulating, and spinning reserve markets. In that model, the VPP consists of RGs and non-RGs as well as flexible DR and tries to maximize its profit considering both supply and demand-sides capability for supplying reserve services. In [11], a bi-level decision-making strategy is proposed for VPPs, in which the competition among VPPs is considered and the rival VPPs compete to attract flexible electric vehicles through a competitive offering strategy. Moreover, in [12], a bi-level decision-making model has been presented for a VPP who is a price-maker to participate in both DA and regulating oligopoly markets with previous forward contracts. Moreover, DR flexibility is considered in the optimization model to manage RGs variability and reduce procurement costs of VPP.

For deploying DR resources, a DR exchange market (DRXM) has been introduced in [13] that prepares trading DR between buyers and sellers. Also, in [14] DRXM has been utilized to efficiently manage the intermittency of renewable generations and prepared a pool-based DRX model into IS's stochastic DA scheduling to augment reliability and decrease procurement costs. In [15], DRXM has been implemented to decrease the punishment costs of the difference between the VPP's cleared power in the DA and real-time dispatch. Although the DRXM effects on the bidding/offering strategies of decision-makers have been investigated in previous literature, some problems exist that should be remarked on properly. How much participating in DRXM can influence the market power of a price-maker VPP as a strategic decision-maker?

To address the above problem, this paper developed a decision-making framework for a price-maker VPP to participate in DA and regulating market (RM) considering DRXM. The strategic VPP optimizes its procurement expenditures by both IDR scheduling and participating in DRXM. In this framework, external DR (EDR) providers submit their bids as supply functions when the dispatched power of the VPP is less than the cleared quantity in the DA market, while the demand function bid manner is applied for EDR providers

when the dispatched power of the VPP is more. To address the impact of bidding behavior of the IDR and EDR providers on the decision-making strategies of the VPP as well as the impacts of the introduction of the DRXM on VPP's market power, some analyses are given. Based on our scientific knowledge, there is no work to address the effect of the DRXM on the power market of strategic VPPs, considering network security constraints. To address this issue, a new index is defined to investigate the impact of trading energy in DRXM on the market power of the VPP. The obtained nonlinear problem is formulated as a bi-level problem that is converted into a linear single-level problem through Karush-Kuhn-Tucker (KKT) optimality conditions and duality theory.

This study tends to investigate the remaining gaps of previous works through the following contributions

- A bi-level decision-making framework for modeling the interaction between a price maker VPP and DSO with network security constraints is proposed through a probabilistic mixed-integer linear programming (PMILP) approach in which the VPP participates in short-term electricity market with considering the flexibility of internal DR resources.
- Interaction between VPP and EDR providers is modeled in a DRXM environment to make up for the real-time power supply-demand deviation of the strategic VPP.
- The impact of the bidding behavior of the IDR and EDR providers on the market power exercised by the VPP is provided through the market inefficiency index (MII).

The remainder of the paper is organized as follows: The overview of the problem description is provided in Section II. In Section III, a bi-level optimization model for the proposed strategic offering of the VPP is built. A case study and sensitivity analysis for assessing the proposed approach to the decision-making problem of the VPP are discussed in Section IV, and at the end, Section V concludes the study of this paper.

II. DESCRIPTION OF THE PROPOSED DECISION-MAKING FRAMEWORK

This paper develops a decision-making framework for a price-maker VPP, in which both internal DRs (IDRs) and DRXM are used to cover the VPP's difference between its cleared power in the DA market and the real-time dispatch. This problem is formulated as a bi-level problem, in which at the upper level, the VPP strives to maximize its expected profit, while at the lower level, DSO seeks to clear both markets to maximize social welfare. The framework of the proposed decision-making framework is shown in FIGURE 1. As observed, the VPP consists of some wind turbines as RGs, dispatchable DGs, and some aggregated flexible loads as internal DRs (IDRs). Each group of IDRs includes several responsive and non-responsive loads that can provide DR services for the VPP. In addition, to decrease the punishment cost on the deviation between cleared power in the DA market and the real-time dispatches, the VPP can provide

DR services from EDR providers in a DRXM environment. EDR providers are more flexible and can supply upward DR resources by shedding their responsive loads or downward DR resources by increasing their consumption.
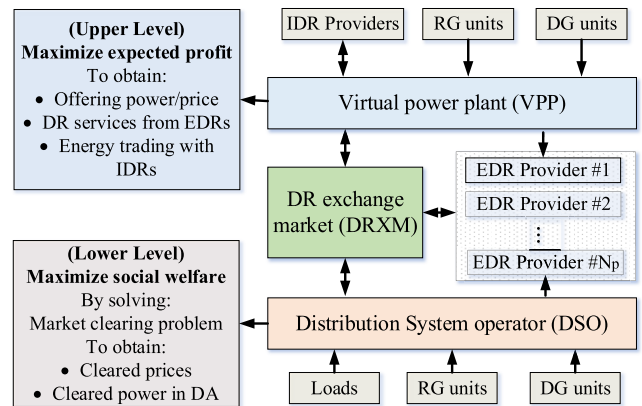

FIGURE 1. The structure of the proposed problem with IDRs and EDRs.

A. DRXM FRAMEWORK

Due to the intermittency and stochastic characteristics of uncertain resources of the VPP such as RGs, demand load and market prices, the VPP may not be capable to deploy the DA cleared energy in the DA market. Therefore, the VPP may confront imbalance penalties in the RM, that which would cause a severe reduction in its profit. In the proposed framework, in order to avoid the negative influences of uncertain resources on the VPP's profit, the VPP can cover its power deviations from two DR resources: IDR resources and EDR resources in the DRXM. Based on these two options, VPP's deviations natured from its uncertainties can be covered and as a result, its regulating penalties will reduce.

Participation of IDR in order to provide DR services is modeled using demand elasticity and offering price signal [16]. Practically, based on the offering price signal, the flexible IDRs adjust their responsive loads and provide DR flexibility for the VPP. In this study, it is assumed that the VPP has a strategic position in the network and acts as a price-maker agent, and therefore it can influence the market clearing price (MCP). Under these conditions, the VPP maximizes its expected profit by modifying the MCP and imbalance penalty payment prevention by using IDR flexibility and also participating in DRXM. In this regard, EDR providers suggest their offers in the DRXM for providing DR services. The offering price signal of the EDRs would be collected and sent to the VPPs through a local market. This surely requires intensive computational power and communication infrastructures; through which the import/export pricing data be transferred through smart meters. DRXM can provide DR options for the VPP to purchase DR services through this local market. Although such EDR services bring stochastic fluctuations to the VPP.

The VPP's decisions are made by considering the offered prices of EDR providers, bids of IDRs, bids of loads, and

the marginal price of DGs as well as RM prices. In this framework, when the total actual output of the VPP is more than their cleared power in the DA market, the VPP can sell its excess power in the DRXM at a price higher than the down-regulating price. On the other hand, when the total actual output power of the VPP is lower than its cleared power in the DA market, it can purchase the shortage in the DRXM at a price lower than the up-regulating price. From a single point of view, through DRXM, the VPP can reduce its energy transaction in the electricity market which means the dependency of the VPP on the network mitigates. Moreover, implementing DR programs for IDRs and also interacting with EDR providers under the DRXM environment not only can reduce the imbalance penalties of the VPP, but also has a severe effect on the grid status. In fact, demand flexibility for providing such DR services as load reduction or increase and consequently supplying loads locally specifically during peak hours can cause alleviate network congestion in the distribution system.

After solving the market-clearing problem, MCP is specified and the share of EDR providers in DR services would be determined. Then, EDR aggregators receive calling signals from the VPP and determine their support in fulfilling the request of the VPP.

During clearing the market, the DSO performs an optimal power flow (OPF) calculation and provides the results of market-clearing for the VPP and other agents. It should be noted that, since the DSO does not own DG units, EDR providers, and also the VPP, it will stimulate the VPP to obtain the cleared market bid by releasing a price. The amount of power exchange with the VPP and distribution system is achieved through an economic dispatch process under the given price.

Considering DRXM with some external loads under the jurisdiction of EDR providers, let's denote the amount of load that EDR providers tend to adjust (i.e., shed or increase) on the DRX trading floor. Here, the total load required for shedding or increasing (q_p) to meet the VPP's energy deviation is given as below:

$$\sum_{p=1}^{N_p} q_p = \begin{cases} q_p^{red} \\ q_p^{aug} \end{cases} \quad (1)$$

where q_p^{red} implies that the EDR providers may offer their customer options for load reduction likewise load curtailment or load shifting and utilizing onsite energy storage. In this case, the EDR providers apply their utility function to receive revenue for the provided energy reduction. Furthermore, q_p^{aug} conveys that the EDR providers may augment their demand and exercise payments by switching to their cost function. In the following, two DR functions for load reduction and load augment for EDR providers are described.

1) COST FUNCTION FOR LOAD INCREASE

when the total generation of VPP is greater than the cleared quantity in DA market, EDR providers will increase their loads, and each EDR provider provides DR services to the VPP and bids a cost function as follows:

$$q_p^{aug}(P_{p,t,\omega}^{aug}, \lambda_{t,\omega}^{aug}) = P_{p,t,\omega}^{aug} \lambda_{t,\omega}^{aug} \quad p = 1, 2, \ldots, N_p \quad (2)$$

where, the cost function $q_p^{aug}(P_{p,t,\omega}^{aug}, \lambda_{t,\omega}^{aug})$ describes the amount of loads that EDR provider p commits to increase when the price is $\lambda_{t,\omega}^{aug}$. $\lambda_{t,\omega}^{aug}$ for the DRXM is determined as:

$$\lambda_{t,\omega}^{aug} = \frac{q_p^{aug}}{P_{p,t,\omega}^{aug}} \quad (3)$$

When the EDR provider augments its load, the bidding price for augmenting the load is obtained from (4).

$$\lambda_{t,\omega}^{aug} = \psi_1 \lambda_{t,\omega}^{dn} \quad (4)$$

After clearing the offers and bids in the DA market, the agents would compensate for their energy shortage in the RM. So, the hourly values of DR services provided by EDR providers to support the VPP's request are determined.

2) UTILITY FUNCTION FOR LOAD REDUCTION

When the output generation of the VPP is less than the cleared quantity in the DA market, EDR providers can bid load reduction (q_p^{red}) in the DRXM. So, the DR utility function for load reduction is considered as:

$$q_p^{red}(P_{p,t,\omega}^{red}, \lambda_{t,\omega}^{red}) = P_{p,t,\omega}^{red} \lambda_{t,\omega}^{red} \quad p = 1, 2, \ldots, N_p \quad (5)$$

Here, $\lambda_{t,\omega}^{red}$ is the bidding price of the EDR provider p. The utility function describes the amount of loads that EDR providers commit to shedding when the price is $\lambda_{t,\omega}^{red}$. Here, $\lambda_{t,\omega}^{red}$ would be determined through the bidding of EDR providers:

$$\lambda_{t,\omega}^{red} = \frac{q_p^{red}}{P_{p,t,\omega}^{red}} \quad (6)$$

It is considered that EDR provider p incurs a reduction price $\lambda_{t,\omega}^{red}$ as given in (7) when it curtails its load demand q_p^{red} ($P_{p,t,\omega}^{red}, \lambda_{t,\omega}^{red}$).

$$\lambda_{t,\omega}^{red} = \psi_2 \lambda_{t,\omega}^{up} \quad (7)$$

B. ASSESSING THE EFFECT OF ENERGY TRADING IN DRXM ON THE MARKET POWER OF THE STRATEGIC VPP

To quantitatively evaluate the impact of VPP's participation in the DRXM on the market power of the strategic VPP, a new assessment index is defined. This index is called the market inefficiency index (MII) and presents the rate of changes in DSO's social welfare when the VPP participates in DRXM rather than when it does not participate in the DRXM.

$$MII = \frac{SW \big|\psi_{1/2} - SW \big|\psi_{1/2}'}{SW \big|\psi_{1/2}} \quad (8)$$

Using this index, DSO can have a more accurate estimation of the market power of the VPP and the social welfare in different conditions. In MII, the difference between the social welfare of DSO in the conditions with a specific augment/reduction price is compared with another value of it.

III. MATHEMATICAL MODEL OF THE PROPOSED BI-LEVEL PROBLEM

In this section, the proposed model for determining the optimal offering strategy of a price-maker VPP is formulated as a bi-level stochastic problem. At the upper level of the problem, the VPP implements DR programs for IDRs and also interacts with EDR providers under DRXM environment to reduce its imbalance penalties. Also, the VPP covers its uncertainties in the RM. In this regard, based on (9) it maximizes its expected profit during the scheduling horizon:

$$Max \sum_{\omega \in \Omega} \pi_\omega \sum_{t \in T} Rev^{DA} + Rev^{IDR} + Rev^{EDR} - Pen^{RM} \quad (9)$$

$$Rev^{DA} = P_{t,\omega}^{DA} \lambda_{n,t} \quad (10)$$

$$Rev^{IDR} = P_{t,\omega}^{IDR} \lambda_{t,\omega}^{IDR} \quad (11)$$

$$Rev^{EDR} = P_{t,\omega}^{aug} \lambda_{t,\omega}^{aug} - P_{t,\omega}^{red} \lambda_{t,\omega}^{red} \quad (12)$$

$$Pen^{RM} = P_{t,\omega}^{dn} \lambda_{t,\omega}^{dn} - P_{t,\omega}^{up} \lambda^{up} \quad (13)$$

The expected profit of the VPP includes the terms including the revenue from selling the amount of cleared energy in the DA market; the next two terms represent the revenue from energy transactions with IDRs and EDRs. The last term refers to the penalty costs for participating in RM.

The amount of increase and reduction prices for trading energy with DRXM is considered as a product of RM prices as given in (14) and (15), respectively.

$$\lambda_{t,\omega}^{aug} = \psi_1 \lambda_{t,\omega}^{dn} \quad (14)$$

$$\lambda_{t,\omega}^{red} = \psi_2 \lambda_{t,\omega}^{up} \quad (15)$$

From (14), it can be seen that when EDR providers augment their energy, the VPP will receive money from them at a price equal to the ratio of the down-regulating price. However, based on (15), the VPP will pay EDR providers with a ratio of up regulating price.

The cleared power in the DA market would be obtained from the power balance equation that is given in (16) which consists of two main parentheses. The first parenthesis consists of the predicted wind power, the DR service purchased from the DRXM, and the energy purchased from up RM. The second parenthesis includes the provided energy for the IDRs and EDRs in DRXM and the sold energy in down RM as in:

$$P_{t,\omega}^{DA} = (P_{t,\omega}^P + P_{t,\omega}^{EDR,red} + P_{t,\omega}^{up}) - (P_{t,\omega}^{IDR} + P_{t,\omega}^{EDR,aug} + P_{t,\omega}^{dn}) \quad (16)$$

Moreover, uncertainties of wind power generation are extracted based on the wind speed through a piecewise linear approximation of active power of wind turbines that can be obtained from scenarios of wind speed based on the wind power curve as follows:

$$P_{t,\omega}^P = P_w^r \cdot \begin{cases} 0, & 0 \le v_\omega \le v_{in} \, or \, v_\omega \ge v_{out} \\ (v_\omega - v_{in})/(v_r - v_{in}), & v_{in} \le v_\omega \le v_r \\ 1 & v_r \le v_\omega \le v_{out} \end{cases} \quad (17)$$

where, v_ω, v_r, v_{in}, and v_{out} indicate the speed at each scenario, the rated speed, cut-in speed, and cut-out speed of the wind turbine, respectively, and P_w^r represents the total rated power of the wind turbine.

DR services that can be purchased/sold from/to the DRXM by the VPP are restricted with the maximum value of DR services provided by the EDR providers as in (18) and (19).

$$P_{t,\omega}^{EDR,aug} \le \bar{P}_{t,\omega}^{EDR,aug} \quad (18)$$

$$P_{t,\omega}^{EDR,red} \le \bar{P}_{t,\omega}^{EDR,red} \quad (19)$$

In the lower level, DSO schedules the distribution network and clears the DA intending to minimize its operating costs. Therefore, the objective of the DSO is defined as follows:

$$Min \sum_{\omega \in \Omega} \pi_\omega \sum_{t \in T} \left[Cost^G + Cost^{VPP} - Income^D \right] \quad (20)$$

$$Cost^G = P_{t,\omega}^G \lambda_t^G \quad (21)$$

$$Cost^{VPP} = \alpha_t P_{t,\omega}^{DA} \quad (22)$$

$$Income^D = P_{t,\omega}^D \lambda_{t,\omega}^D \quad (23)$$

The operating cost of DSO includes the costs that it should pay to DGs and to the VPP for the energy that purchased from them. Also, the DSO can achieve some income from selling energy to the loads. The lower level of the problem is limited by the following constraints. Each constraint is separated with ":" and its associated dual variables. The power flow equations are used to model the real-time operation of the distribution network for each scenario and at each time interval [17]. The power balance equation at node n of the distribution network is represented by equation (24).

$$P_{t,\omega}^G + P_{t,\omega}^{DA} - P_{t,\omega}^D = \sum_{r=1}^{N_B} fl_{t,\omega} : \varepsilon_1 \quad (24)$$

where $fl_{t,\omega}$ shows the power flow from each line. Here, the linearized power flow equation is used to formulate the VPP power flow that is extracted from [17] as:

$$f_{l,t,\omega} = B_k(\delta_{s,t,\omega} - \delta_{r,t,\omega}) : \varepsilon_2 \quad (25)$$

To satisfy network congestion, the line flow should be limited as:

$$-f_l^{max} \le f_{l,t,\omega} \le f_l^{max} \quad (26)$$

The production of units and required demand of loads are restricted by the following limitations:

$$0 \le P_{t,\omega}^G \le \bar{P}_G : \varepsilon_7, \varepsilon_8 \quad (27)$$

$$0 \le P_{t,\omega}^D \le \bar{P}_D : \varepsilon_9, \varepsilon_{10} \quad (28)$$

Moreover, the nonlinear term $P_{t,\omega}^{DA} \lambda_{n,t}$ is linearized using strong duality theory and some relaxation methods that can be found in [18]. The bi-level problem would be recast to a single level using KKT optimality constraints as in [16].

$$\alpha_t - \varepsilon_1 - \varepsilon_5 + \varepsilon_6 = 0 \quad (29)$$

$$0 \le \varepsilon_3 \perp f_l^{max} - f_{l,t,\omega} \ge 0 \quad (30)$$

$$0 \leq \varepsilon_4 \perp f_{l,t,\omega} + f_l^{\max} \geq 0 \qquad (31)$$

$$\varepsilon_{1,s} + B_k \varepsilon_{2,s} - B \varepsilon_{2,r} - \varepsilon_3 + \varepsilon_4 = 0 \qquad (32)$$

$$\lambda^G - \varepsilon_1 - \varepsilon_7 + \varepsilon_8 = 0 \qquad (33)$$

$$\lambda_{t,\omega}^D - \varepsilon_1 - \varepsilon_9 + \varepsilon_{10} = 0 \qquad (34)$$

IV. CASE STUDY AND NUMERICAL RESULTS

A. CASE STUDY AND INPUT DATA

The proposed model is implemented on the modified 33-bus distribution system given in [19], and the numerical results are presented to analyze the energy arbitrage of the VPP with the contribution of IDR flexibility and also energy trading of the VPP in DRXM. The VPP is located at bus 14 of the distribution system and includes aggregated wind turbines as RGs, dispatchable DGs as well as responsive and non-responsive loads. The forecasted values of load and wind power of the VPP are shown in FIGURE 2. Also, up and down RM prices are obtained from Nordpool [20] and presented in FIGURE 3. Based on the historical data on wind power, RM prices, and loads, 200 scenarios are generated for each random variable using the related probability density function [21]. After combining scenarios using a scenario tree [22], the number of scenarios is reduced to obtain efficient scenarios by applying k-means algorithm [23].

The economic model presented in [24] is used for the participation of IDRs in price-based DR programs. The IDRs' curtailing/shifting loads are modeled based on demand elasticity [25] and electricity prices.

In addition, EDR providers are considered, that provide DR services for the VPP through DRXM. When the VPP's dispatch power is greater than its cleared power in the DA market, each EDR provider applies its cost function and when the VPP's dispatch power is less than its cleared power in the DA market, the EDR providers switch to their utility function. The proposed decision-making problem is solved using MILP using CPLEX under GAMS software [25], on a computer with a 6-core 3.47 GHz Intel(R) Xeon(R) X5690 processor and 192 GB of RAM.

B. NUMERICAL RESULTS

Based on the offered price in DRXM, EDR providers determine the amount of DR services that they can make in real-time and send their offers to the VPP.
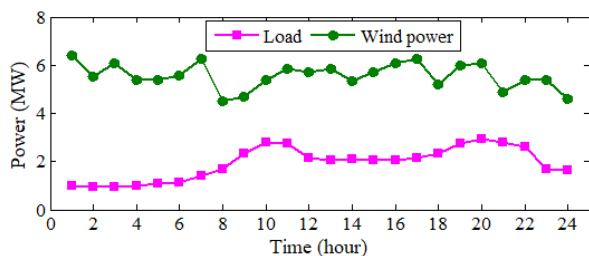
FIGURE 2. Forecasted hourly load and wind power of the VPP.

EDR providers can provide DR services in two terms by using DR reduction and DR augment based on the VPP's
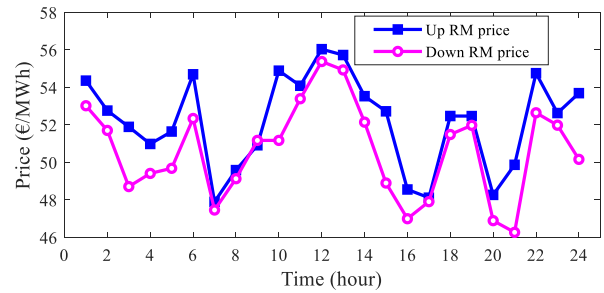
FIGURE 3. Forecasted up and down RM prices.

required energy that may not be cleared in the DA market. : FIGURE 4 shows the cleared power and cleared prices of the VPP in the DA market in three levels of EDR services. In his figure, the level of IDR participants in DR programs is fixed at 40%. As observed, when the VPP does not trade in the DRXM, the VPP submits its total generation to the DA market. But through DRXM, the VPP can provide the remaining bid deviations from the DRXM. In some hours, for example, during the early hours of the day, the VPP offers lower energy to the DA market because the VPP tends to arbitrage on the price differences and sell energy in DRXM at higher prices than that of in the DA market. In some other hours such as 8:00 and 20:00, the cleared DA energy of the VPP is higher compared with the case where EDR service is considered. Low prices in DRXM encourage the VPP to purchase DR services aggressively and further reduce the energy arbitrage of the VPP in the DA market; in this regard, the VPP can achieve more profit. By increasing EDR services, more values of the energy mismatch of the VPP are balanced through the DRXM. FIGURE 4 (b) shows cleared price of the DA market for three levels of EDR services. By providing EDR services, cleared price of the VPP remains the same in most periods and augments in a few hours. Compensating the deviated energy from the DRXM causes a general increment in cleared price and consequently, the VPP achieves more market power.

The excess and shortage of energy of the VPP traded in the RM is demonstrated in FIGURE 5. With the participation of the VPP in the DRXM, it prefers to sell the surplus energy to the DRXM at a higher price instead of selling it with the cheap down-regulating price, thus the amount of surplus energy sold to down RM reduces. **FIGURE 5** (b) depicts the excess and shortage of energy of the VPP traded in the RT market. As observed, without DRXM, an aggressive energy arbitrage in the RT market for selling the surplus energy in the real-time market occurs. While, when EDR services exist, with the participation of the VPP in the DRXM, it prefers to sell the surplus energy to the DRXM at a higher price instead of selling it with a cheap down-regulating price, thus the amount of surplus energy sold to down RM reduces. Instead, **FIGURE** 5 (b) shows that the energy deficit of the VPP increases when EDR services exist. The reason is that when EDR service increases, EDR loads may purchase more energy from the VPP, and as a result, the amount of VPP's energy deficit increases in some hours that should be

compensated from the up RM. It is seen that the trend of energy deficit follows the RM prices. As seen, during peak prices, the VPP has a high sale share during peak periods of the regulating prices and also when the VPP has energy excess. **FIGURE 5** (b), indicates that when EDR services exist, the VPP confronts with more energy deficit, because, EDR loads may tend to supply their required demand through DRXM due to the fair prices.
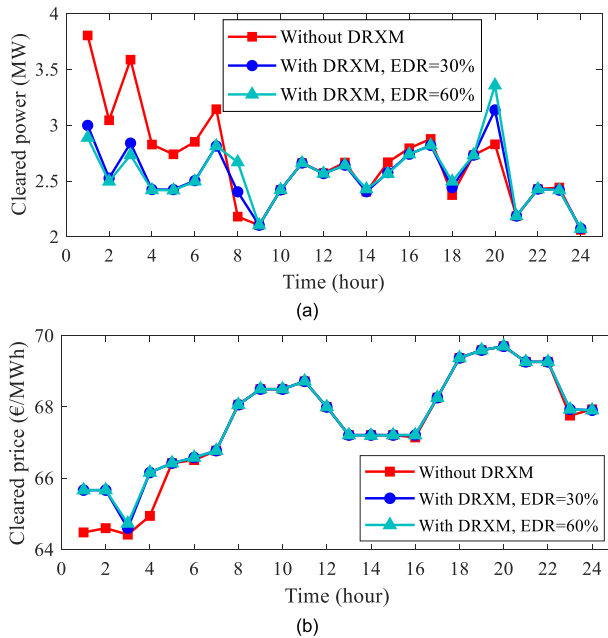

FIGURE 5. Trading energy in the RM, (a) surplus energy and (b) deficit energy.

FIGURE 4. (a) Cleared power and (b) cleared price in the DA market.

To investigate the flexibility of the proposed framework for the VPP to purchase EDR services from DRXM, a sensitivity analysis is executed for the values of MII to obtain its effect on the market power of the VPP. FIGURE 6 presents the MII with and without EDR services. With trading services through DRXM, MII reduces which implies trading EDR services can enable EDR providers to preserve their economic surplus. However, with higher participation of EDR providers in DRXM, the values of MII increase, which shows the operating cost of the distribution network increases. In both diagrams, with increasing the augmenting (Ψ_1) and reducing (Ψ_2) price, the decrement in social welfare occurs more. That is because allowing EDR providers make the social welfare does not improve, and so the decrement in required demand occurs.

The expected profit of the VPP in different values of Ψ_1 and Ψ_2 is presented in FIGURE 7. With increasing Ψ_1, the VPP can take advantage of selling energy in DRXM at a higher price rather than RM. However, such price increment is not so much high that the EDR providers may favor these fair prices and supply its required energy from independent producers. Providing the expected profit of the VPP at different prices for different values of Ψ_1 and Ψ_2 would bring
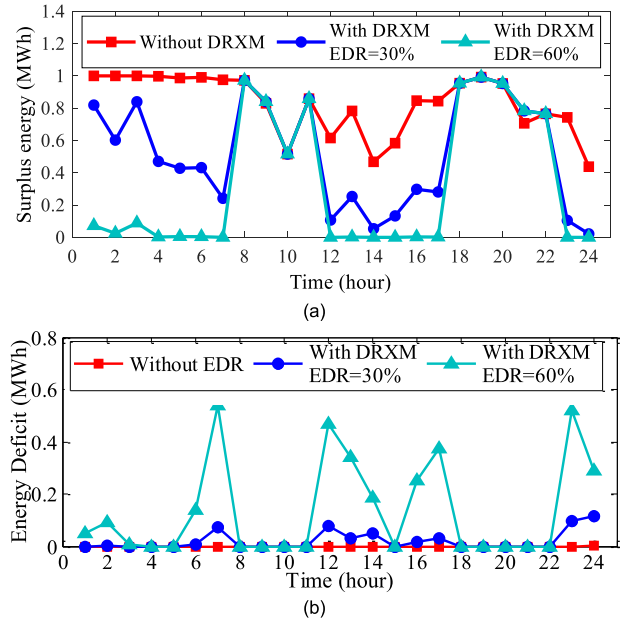
a profile for the VPP operator to choose which offered price for EDR services would be more beneficial.

Energy trading between the VPP through DRXM in three levels of EDR services is illustrated in FIGURE 8. The positive values present the sold EDR services to the DRXM that the EDR providers offered during midnight and afternoon, where the EDR loads augment their demand during that time. During peak periods, EDR providers offer DR services such as load reduction that presents with a negative sign. With the increasing participation of EDR providers, trading energy with the VPP augments that is due to providing cheaper EDR services through the DRXM.

To provide the effect of different values of DRXM prices on the decision-making of the VPP, the profile for total cleared energy and expected profit of the VPP in different IDR and EDR participants are given in FIGURE 9.

The VPP as a decision-maker can decide which IDR percentage and which trading energy with the DRXM would be more beneficial for it. As observed from FIGURE 9 (a), with increasing IDR participants, the VPP can sell the excess energy to IDRs, thus the cleared energy of the VPP in DA is relatively reduced. Moreover, it is observed that for up to 30% of EDR participants in the DRXM, the DA cleared power reduces substantially, while, it remains constant for higher EDR participants to exercise the market power of the VPP. FIGURE 9 (b) shows the slight reduction of VPP's profit with increasing IDR services that is due to load shifting of the internal loads to off-peak hours that are supplied with a low value of nodal prices. However, with increasing EDR services, the VPP proactively trades energy in DRXM and pursues profitability. The reason is that EDR providers offer energy augments at higher prices than the RM ones. During
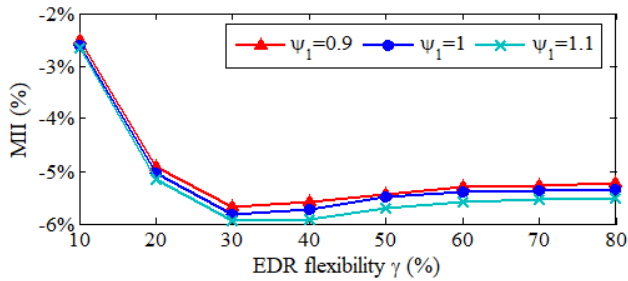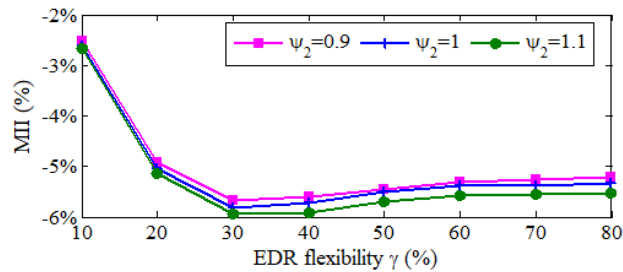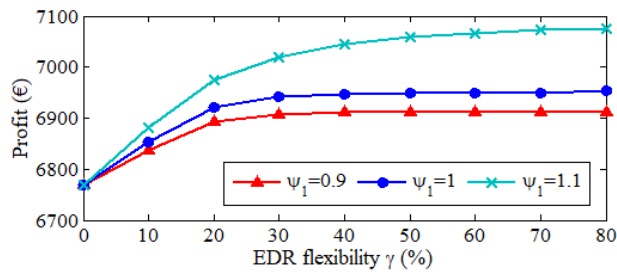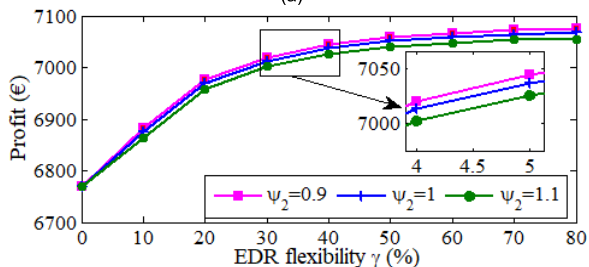
FIGURE 6. MII in different levels of EDR, (a) $\Psi_2 = 0.9$ and (b) $\Psi_1 = 1.1$.

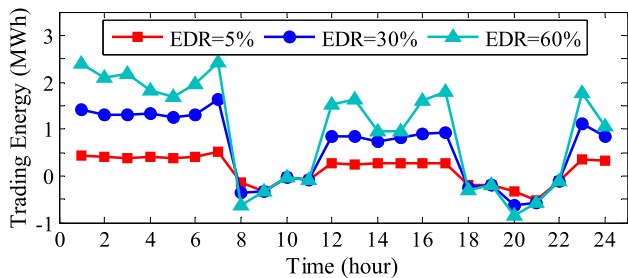FIGURE 7. Expected profit of the VPP in different levels of EDR, (a) surplus energy and (b) deficit energy.

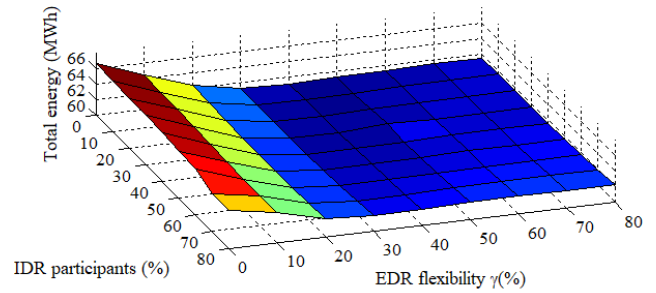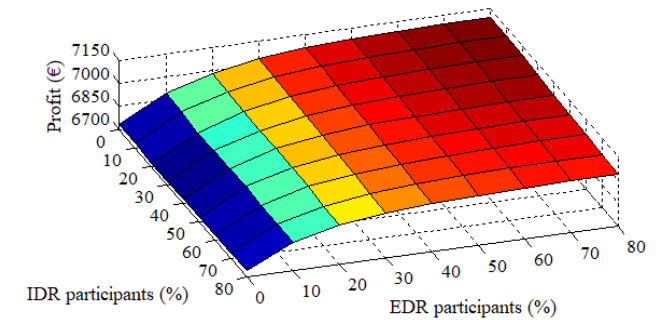FIGURE 8. Energy trading of the VPP in the DRXM in different levels of EDR services.
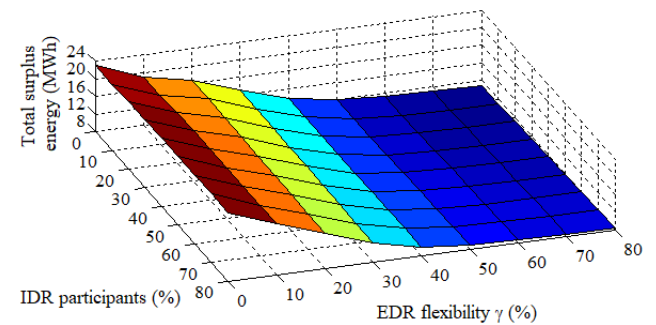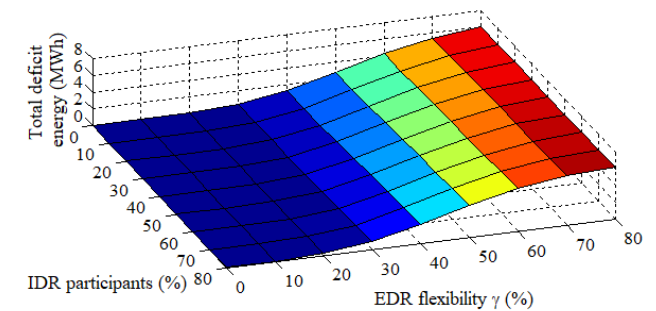

FIGURE 9. (a) Total cleared energy and, (b) expected profit of the VPP in different levels of IDR and EDR services.

FIGURE 10. Total energy compensated in RM in different levels of IDR and EDR services, (a) surplus energy and, (b) deficit energy.

those periods, the VPP strives to take advantage of energy arbitrage with EDR providers.

FIGURE 10 shows total energy traded in the RM in different levels of IDR percentage and EDR services to cover the surplus and deficit energy of the VPP in real-time. With increasing EDR services, a flexible option is provided for the VPP in confronting selling the surplus energy. Therefore, instead of being incurred by the undesired penalties, the VPP

sells its surplus power in DRXM at higher prices to take more advantage. In this regard, the VPP may confront an energy deficit, so it enters the RM to purchase its energy deficit. However, being mentioned that the VPP purchases its energy deficit from RM only when the EDR providers do not submit energy reduction. This is approved by comparing FIGURE 7 (b) and FIGURE 8.
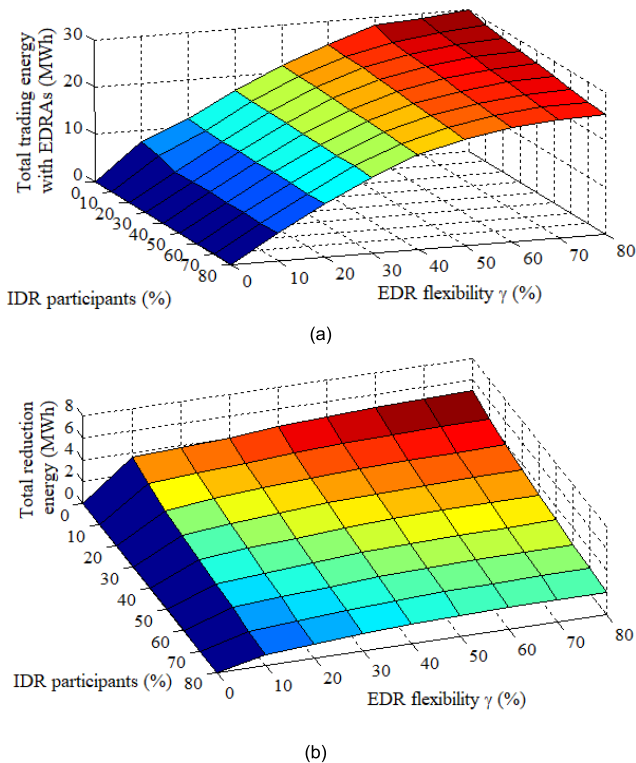

(a)

(b)

FIGURE 11. Total trading energy in DRXM (a) augment and (b) reduction.

FIGURE 11 shows the total energy reduction and energy augment that the VPP traded in the DRXM in different levels of IDR percentage and EDR services. With increasing IDR percentage, both energy reduction and augmentation reduce that is because the VPP addresses its uncertainty through the IDRs, while the opposite occurs when more EDR service is provided for the VPP. This clearly shows that with trading in DRXM in both cases, the VPP can cover energy deviations and avoid the energy curtailment of its RGs.

V. CONCLUSION

This paper proposed a bi-level stochastic model for the optimal bidding strategy of a price maker VPP. In this model, in addition to IDR services, a DRXM is introduced to cover deviations of RGs' productions of the VPP in real-time to obtain more profit. In this framework, the VPP can trade in DRXM to augment its selling in the DA market, while reducing its regulating penalties in the RM. Moreover, MII as a market-based index is defined to examine the impacts of trading a strategic VPP in the DRXM on the social welfare of DSO in different conditions. The proposed bi-level problem is converted into a linear single-level MILP model

using KKT optimality conditions and strong duality theory. Numerical simulation shows that trading in DRXM not only improves the profit of the VPP but also guarantees the optimal operational cost of the distribution market. Furthermore, the impact of different levels of IDR services on the optimal decision-making of the VPP is evaluated through sensitivity analysis. This analysis shows that in high EDR participants, the expected profit of the VPP augments about 3% which is a substantial value for the one-day scheduling horizon. It is also shown that the DRXM provides a flexible option for the VPP in reducing the surplus sold energy in RM. Providing the expected profit of the VPP at different prices for EDRs would bring a profile for the VPP to choose which offered price to EDR providers would be more beneficial.

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