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Ex-ante Dynamic Capacity Withholding Assessment of Virtual Power Plants in Local Electricity Market

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Abstract
This paper introduces an algorithm for the Local Electricity Market Operator (LMO) in distribution networks to assess dynamic capacity withholding by Virtual Power Plants (VPPs). Its main contribution is providing ex-ante indices to evaluate this withholding. The paper also quantitatively analyzes how LMO's risk aversion impacts the market power exerted by these withholding groups. The day-ahead market problem is tackled in three stages: estimating VPPs' optimal withholding strategy, determining optimal system scheduling, and analyzing network configuration changes to reduce market power. The results indicate that the exercise of market power by capacity-withholding groups increases the LMO's cost by an average of 35%. Furthermore, the simulation of collusion in the proposed model reveals that the market power of capacity-withholding groups increases by an average of 5% under the risk-averse behavior of LMO. Moreover, the results demonstrate that proactively restructuring the network according to the proposed algorithm on the 123-bus IEEE test system can reduce the market power of capacity-withholding groups and lower the average index to 25.12%.

Keywords
Local electricity market; Active distribution network; Virtual power plants; Dynamic capacity-withholding; Bidding strategy.

1. Introduction

In recent years, the development of distributed energy resources in distribution networks has changed the nature of these networks from passive to active [1]. This change has caused the emergence of new players such as virtual power plants (VPPs) in distribution networks [2]. Therefore, the need for a platform for trading electrical energy at the level of distribution networks has increased [3]. Numerous studies have recently been conducted to achieve this goal, focusing on the concept of local electricity markets (LEMs), including the concept of capacity withholding by players participating in the market [4]. Capacity withholding in a power market refers to the deliberate act of withholding or reducing the generation capacity of market participants. It is a strategic behavior aimed at influencing market conditions and increasing profits [5]. VPPs can use their market power to increase prices by using capacity-withholding strategies [6]. The local market operator (LMO) should detect multiple capacity-withholding groups to contribute to these procedures. The withholding assessment can be accomplished by employing ex-ante or ex-post indices. The ex-ante indices are based on market structure and can be calculated by considering the number of players and the market share assigned to each of them. The ex-post indices are calculated by comparing the current market to a completely competitive market [7]. The withholding process of VPPs can be categorized into "economic withholding" and "capacity-withholding" processes that are performed by increasing the bid prices and reducing the output of VPPs, respectively. Furthermore, all withholding processes can be exercised for a single period or a multi-period of the operational horizon, known as the "static-withholding process" and "dynamic-withholding process", respectively. Dynamic capacity-withholding processes can be categorized into implicit and explicit sub-processes. In the implicit category, there is no direct relationship between VPPs, whereas, in the explicit category, the market price is completely controlled by non-utility energy generation facilities [8-10]. The research references are divided into the following three main groups:

1) Papers that have investigated the capacity (economic or physical) withholding from a corrective actions point of view,
2) Papers that have investigated the capacity (economic or physical) withholding of non-intermittent generation units from a preventive actions point of view,
3) Papers that have investigated the capacity (economic or physical) withholding of emerging generation units (VPPs, aggregators, retailers) from a corrective actions point of view.

In the first category of papers, only the topics of capacity withholding after the occurrence are examined. Ref. [4] proposed multiple dynamic capacity-withholding indices for LEM considering reserve procurement services. The model considered the impacts of the withholding processes of VPPs on the flexibility of the distribution system. However, the impacts of reconfiguration of the system's topology on the withholding processes were not modeled. Ref. [8] investigated the capacity withholding of power plants in the wholesale electricity market (WEM). The maintenance program of power plants was studied as a tool to withhold the capacity of units from the market. Ref. [9] examined the possibility of collusion between power plants and transmission system companies on a 24-bus network and an index was provided for its evaluation. Ref. [10] investigated the economic withholding of generation companies in the electricity market by using a SCAD-logit model. Ref. [11] reported that, in addition to preventing the dynamic capacity withholding, one of the things that might be used by the generation units was the failure to provide the rate of increase and decrease of power by these units. Ref. [12] used machine-learning tools to identify dynamic capacity withholding in the electricity market among producers.

In the second group of articles, papers used different tools for simulating the market conditions to prevent capacity withholding in the electricity market. Ref. [13] evaluated the dynamic capacity withholding of thermal units from a preventive point of view. The paper showed how the thermal units had taken the market prices out of the competitive mode and earned a high profit by their capacity withholding. Ref. [14] investigated the potential of dynamic economic withholding of generation units using Game Theory (GT) tools to create a cartel and influence market prices. Ref. [15] explored the declaration of intentional disruptions is examined in this paper as a mechanism that causes capacity withholding. However, no index is provided by the authors to enable the market operator to conduct a quantitative evaluation. Ref. [16] employed the capacity-withholding index to investigate the possibility of capacity withholding by traditional power plants participating in the wholesale energy market. Ref. [17] utilized an ex-ante Customized Market Operation (CMO) indicator; this paper assessed how conventional power plants exercise market power individually. Nevertheless, the analysis failed to consider the formation of collusion groups or the dynamic capacity withholding by conventional power plants. Ref. [18] reported that the economic-withholding of generation units in the direction of increasing prices could be identified by analyzing the market prices and marginal profit of generation units. Ref. [19] examined the electricity market prices in Italy between 2012 and 2014. The authors considered four factors: a) discretionary market power, b) generation and transmission network constraints, c) system cost profile, and d) dynamic capacity withholding of generation units (or implicit collusion between units). Ref. [20] described the Nash-Cournot model to identify the economic withholding occurring by the generation units in a non-competitive market. Ref. [21] provided a model to evaluate the capacity withholding of fossil fuel units against renewable units in the market; however, no index was provided to evaluate the model. Ref. [22] presented an equilibrium optimization method to analyze the market power of prosumers. This paper used the Cournot model of GT for market analysis and modeling the problem. The authors of Ref. [23], by studying the presence of renewable energy sources in the day-ahead and real-time markets, concluded that the random and variable nature of these generation units could be utilized to prevent the capacity-withholding process of fuel-based facilities. Ref. [24] introduced a strategic player that had several non-intermittent power plants and wind power plants. Using the Stackelberg model and a two-level optimization process, the profit of generators in the energy and reserve markets was maximized. Ref. [25] investigated the dynamic capacity withholding between generation units in dynamic mode. The problem was modeled in four levels and provided an index to evaluate the possibility of dynamic capacity withholding. In the third group of articles, researchers examined the occurrence of capacity withholding by new players in electricity markets considering the interactions of microgrids. Ref. [26] presented a model of the static capacity withholding of the VPP in a distribution network. The authors modeled the problem of capacity withholding in the electricity market using a stochastic model and using the capacity-withholding index. Ref. [27] examined the potential influence of electric energy storage systems on the electricity market using an ex-post approach. The findings of this study indicated that the increased market power of these players enabled them to exert influence through economic withholding strategies. Ref. [28] studied the problem of cooperation between a set of microgrids under the title of a group of microgrids. The following issues identify the main research gaps:

- The majority of studies concerning collusion in electricity markets have focused on traditional power plants participating in the wholesale electricity market, with limited research exploring the connection to local electricity markets. This issue is significant given that the inherent nature of emerging players in the distribution network differs substantially from that of traditional power plants, thus necessitating independent studies specifically addressing local electricity markets,
- The impact of a risk-averse market operator's behavior on increasing market power and capacity-withholding groups has not been quantitatively investigated,
- In studies based on preventative methods, which are often market simulation-based, it is necessary to undertake measures aimed at reducing the market power of capacity-withholding groups.

As shown in Fig. 1, it is assumed that the market operator is an independent entity from the distribution company. This institution is known as an independent local market operator. According to Fig. 1, LMO considers the following inputs for its optimization problem: (1) received bids from VPPs, and (2) the operational status of independent distributed energy resources within its managed distribution network. Additionally, part of the required power may be procured from the upstream grid depending on WEM conditions. Using these inputs, the LMO solves the LEM clearing problem in a day-ahead timeframe with the objective of social welfare maximization.

Therefore, the problem of the dynamic capacity withholding of VPPs is analyzed. In this paper, the potential of the dynamic capacity withholding of VPPs in the active distribution network market is investigated and an index is provided for the market operators to make a proper evaluation of the received offers. The main contributions of this paper are:

- Studying the dynamic capacity-withholding of VPPs present in active distribution network markets to compare and quantitatively analyze the influence of the withholding groups' behavior in these markets using an index,
- Analysis of the risk caused by generation resources with uncertainty, LEM exploitation on the market settlement process, and the extent of its effect on the increase of the capacity-withholding index in the distribution market,
- The proposed structure is a preventive model and enables the market operator to identify the potential of the dynamic capacity withholding occurrence and the increase in the market cost,
- The effect of network structure modification on market outcomes has been analyzed based on the fact that the structural constraint of the network also increases the market power of capacity-withholding groups.

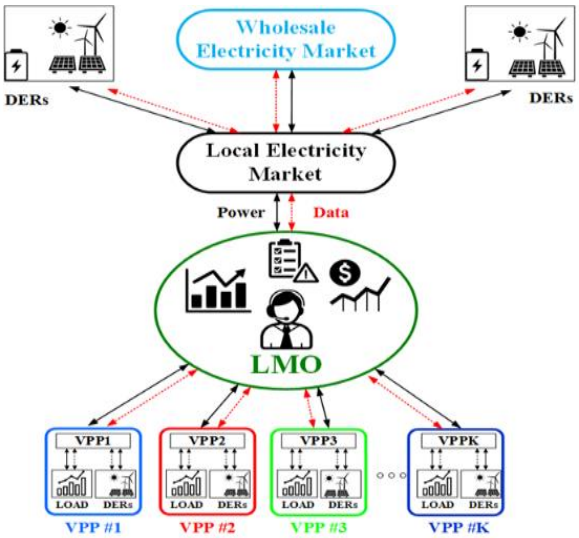

Fig. 1. The electricity transactions and data exchanges of LEM with VPPs.

The remainder of the paper is organized as follows: the problem description is presented in Section 2, the solution methodology is illustrated in Section 3, the numerical results are provided in Section 4, and the conclusions are given in Section 5.

2. Problem Modeling and Formulation

2.1. VPP modeling

In this paper, the authors studied the commercial VPP to participate in LEM to maximize its profit. VPPs participate in the day-ahead electricity market according to their generation resources and internal loads.

2.2. Proposed framework

According to Fig.2 in the first stage, the strategies for participating in the market of VPPs are obtained from the day-ahead market problem. LMO solves this problem from VPPs' point of view to obtain the capacity and price of VPPs in full competition mode. Then, it calculates the cost of supplying the required energy of the system in the state of complete competition, as well as the formation of colluding groups, and obtains the market's capacity-withholding index for the day-ahead market. In the context of perfect competition, each VPP, when making decisions, solely focuses on solving its internal price-based unit commitment (PBUC) problem based on its local marginal cost. However, according to [26,29] under collusive conditions, the members of a capacity-withholding group make decisions as a single unified player, basing their actions on the maximum local marginal cost among the group's members. More accurately, the collusive group aims to maximize the profits of all members involved.

Finally, LMO analyzes the effect of changing the network configuration on the results of the previous stage.

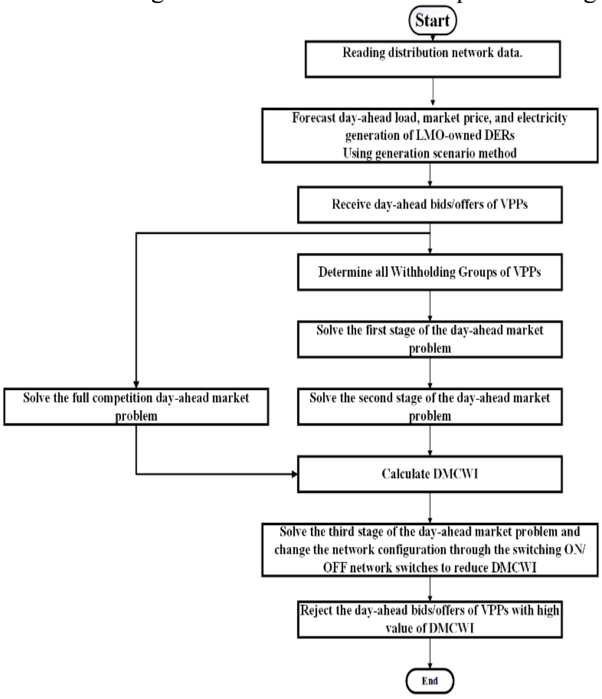

Fig. 2. The Flowchart of the proposed algorithm.

2.3. Day-ahead market optimization problem

2.3.1. First stage of the day-ahead market optimization problem

First, LMO simulates the VPP's profit optimization process in the day-ahead horizon and then explores their possible dynamic capacity-withholding groups. Here, it is assumed that each VPP decides to obtain maximum profit without collusion with other VPPs. Hence, the LMO solves the PBUC problem of each VPP by considering their constraints. The objective function of this problem for VPPs can be presented as Eq. (1):

$$Max\ Z_{VPP}^{DA} = \sum_{\omega} \pi_{\omega} \sum_{t\in\Omega^T} [\lambda_{t\omega}^{DA} p_t^{DA} \Delta t + \sum_{d\in\Omega^D} U_{dt}^{D} p_{dt\omega}^{D} \Delta t - \sum_{c\in\Omega^c} (C_c^{C,F} + C_c^{C,V} p_{ct\omega}^{C} \Delta t), \forall \omega \in \Pi^{DA} \quad (1)$$

The objective function of each VPP is divided into three main parts:

- $\sum_{t\in\Omega^T}\lambda_{t\omega}^{DA}p_t^{DA}\Delta t$: Income/expense from the sale/purchase of power to/from the day-ahead market. $\lambda_{t\omega}^{DA}$ is the market power price in each scenario at time t.
- $U_{dt}^{D}p_{dt\omega}^{D}\Delta t$: Income from the sale of energy to the internal loads of the VPP. U_{dt}^{D} is the price of power sold to consumers at time t.
- $C_c^{C,F}+C_c^{C,V}p_{ct\omega}^{C}\Delta t$: Operating cost of fossil units of each VPP. $C_c^{C,F}$ and $C_c^{C,V}$ are fixed and variable costs of each conventional unit.

It is worth noting that according to Ref. [5], the cost of renewable units and storages can be omitted in the operation of VPP. The VPP optimization objective function for the day-ahead horizon has the following constraints [26]:

A. Electrical power balance constraint in connection point to the distribution network

$$\sum_{c\in\Omega_n^C}p_{ct\omega\gamma}^{C}+\sum_{r\in\Omega_n^R}p_{rt\omega}^{R}+\sum_{s\in\Omega_n^s}(p_{st\omega}^{S,D}-p_{st\omega}^{S,C})-$$
$$\sum_{\ell,s(\ell)=n}p_{\ell t\omega}^{L}+\sum_{\ell,r(\ell)=n}p_{\ell t\omega}^{L}=p_{n,t,\omega}^{M}+\sum_{d\in\Omega_n^D}p_{dt\omega}^{D} \tag{2}$$
$$\forall n\in\Omega^M,\forall t\in\Omega^T,\forall\omega$$

Eq. (2) includes the generation power of non-intermittent units $\sum_{c\in\Omega_n^c}p_{ct\omega}^{C}$, the generation power of renewable units $\sum_{r\in\Omega_n^R}p_{rt\omega}^{R}$, the charging and discharging power of VPP storage devices $\sum_{s\in\Omega_n^s}(p_{st\omega}^{S,D}-p_{st\omega}^{S,C})$, transmission power to the internal network lines of the VPP $-\sum_{\ell,s(\ell)=n}p_{\ell t\omega}^{L}$, and the power received from the internal network lines of the VPP $\sum_{\ell,r(\ell)=n}p_{\ell t\omega}^{L}$. Further, this equation includes the power injected into the grid or received from the grid in the day-ahead market, as well as the internal loads of the VPP.

B. Electrical power balance constraint in other nodes of VPP's internal network

$$\sum_{c\in\Omega_n^C}p_{ct\omega}^{C}+\sum_{r\in\Omega_n^R}p_{rt\omega}^{R}+\sum_{s\in\Omega_n^s}(p_{st\omega}^{S,D}-p_{st\omega}^{S,C})-$$
$$\sum_{\ell,s(\ell)=n}p_{\ell t\omega}^{L}+\sum_{\ell,r(\ell)=n}p_{\ell t\omega}^{L}=\sum_{d\in\Omega_n^D}p_{dt\omega}^{D} \tag{3}$$
$$\forall n\in\Omega^N\setminus n\in\Omega^M,\forall t\in\Omega^T,\forall\omega$$

For other buses of the VPP, the power balance constraint can be considered according to Eq. (3) that includes the generation power of non-intermittent units $\sum_{c\in\Omega_n^c}p_{ct\omega}^{C}$, the generation power of renewable units $\sum_{r\in\Omega_n^R}p_{rt\omega}^{R}$, the charging and discharging power of VPP storage devices $\sum_{s\in\Omega_n^s}(p_{st\omega}^{S,D}-p_{st\omega}^{S,C})$, transmission power to the internal network lines of the VPP $-\sum_{\ell,s(\ell)=n}p_{\ell t\omega}^{L}$ and the power received from the internal network lines of the VPP $\sum_{\ell,r(\ell)=n}p_{\ell t\omega}^{L}$. It also includes the internal loads of the VPP.

C. Others constraints

Eq. (4) represents the limitation related to the amount of power that can be injected by each VPP at the point of connection to the distribution network:

$$P_n^{\min,M}\le p_{nt\omega}^{M}\le P_n^{\max,M}\ ,\forall n\in\Omega^M,\forall t\in\Omega^T,\forall\omega \tag{4}$$

Eq. (5) and Eq. (6) express the constraints related to the operation of non-intermittent units owned by VPP.

$$P_c^{\min,C}\le p_{ct\omega\gamma}^{C}\le P_c^{\max,C}\ \forall c\in\Omega^C,\forall t\in\Omega^T,\forall\omega \tag{5}$$

$$-R_c^{C,D}\Delta t\le p_{ct\omega}^{C}-p_{c(t-1)\omega}^{C}\le R_c^{C,U}\Delta t \tag{6}$$
$$\forall c\in\Omega^C,\forall t\in\Omega^T,\forall\omega$$

Eq. (7) establishes the energy balance in the storage units bounded by the corresponding energy capacities in Eq. (8). Eq. (9) and Eq. (10), which limit the charging and discharging power levels of storage units, respectively. Eq. (11) states that the power generation of stochastic renewable generating units should be lower than or equal to the available one. For $\forall s\in\Omega^S,\forall t\in\Omega^T,\forall\omega$:

$$e_{st\omega}^{S}=e_{s(t-1)\omega}^{S}+\eta_s^{S,C}p_{st\omega}^{S,C}\Delta t-\frac{p_{st\omega}^{S,D}}{\eta_s^{S,D}}\Delta t \tag{7}$$

$$E_{st}^{\min,S}\le e_{st\omega}^{S}\le E_{st}^{\max,S} \tag{8}$$

$$0\le p_{st\omega}^{S,C}\le P_s^{\max,S,C} \tag{9}$$

$$0\le p_{st\omega}^{S,D}\le P_s^{\max,S,D} \tag{10}$$

$$0\le p_{rt\omega}^{R}\le P_{rt\omega}^{R} \tag{11}$$

2.3.2 Second stage of the day-ahead market optimization problem

In this stage, the LMO should solve the problem of supplying the energy of the day-ahead market loads to maximize social welfare for the current topology of the distribution system. The objective function of the LMO in the time horizon of the day-ahead market is according to Eq. (12) for the current topology of the distribution system.

$$Min\ Z_{LMO}^{DA} = \sum_{\omega\in\Omega^{\omega}} \pi_{\omega}\zeta_{\omega} + \beta\cdot[\rho - \frac{1}{1-\alpha}\sum_{\omega\in\Omega^{\omega}}\pi_{\omega}\mu_{\omega}] \quad (12)$$

$$\zeta_{\omega} = \sum_{t\in\Omega^{T}}[\sum_{i\in\Omega^{VPP}}(\lambda_{t\omega i}^{DA} p_{t\omega i}^{DA}\Delta t) + \sum_{g\in\Omega^{G}}(G_{g}^{G,F} + G_{g}^{G,V} p_{gt\omega}^{G}\Delta t) \quad (13)$$

$$+\sum_{r\in\Omega^{R}} U_{rt}^{R,LMO} p_{rt\omega}^{R,LMO}]$$

$$-\zeta_{\omega} + \rho - \mu_{\omega} \le 0 \ \forall\omega\in\Pi^{DA} \quad (14)$$

$$0 \le \mu_{\omega} \ \forall\omega\in\Pi^{DA} \quad (15)$$

According to Eqs. (12) - (15), the objective function of the LMO consists of four parts:

- The cost/income resulting from the purchase/sale of power from/to VPPs participating in the day-ahead electricity market: $\sum_{t\in\Omega^{T}}\sum_{i\in\Omega^{VPP}}(\lambda_{t\omega i}^{DA} p_{t\omega i}^{DA}\Delta t)$.
- The operating cost of non-intermittent units owned by LMO: $\sum_{g\in\Omega^{G}}(G_{g}^{G,F} + G_{g}^{G,V} p_{gt\omega}^{G}\Delta t)$.
- The cost of operating renewable units owned by LMO: $\sum_{r\in\Omega^{R}} U_{rt}^{R,LMO} p_{rt\omega}^{R,LMO}$.
- Modeling the risk caused by the available resources: $\beta\cdot[\rho - \frac{1}{1-\alpha}\sum_{\omega\in\Omega^{\omega}}\pi_{\omega}\mu_{\omega}]$.

The constraints are similar to the VPP problem, but their details are not presented for the sake of space. A day-ahead markets capacity-withholding index ($DMCWI^{DA}$) for the day-head operational scheduling is proposed as Eq. (16):

$$DMCWI^{DA} = \frac{\left|Z_{LMO}^{DA-FC} - Z_{LMO}^{DA}\right|}{Z_{LMO}^{DA-FC}} \quad (16)$$

Where, Z_{LMO}^{DA} is calculated in the second stage problem of the day-ahead market, and Z_{LMO}^{DA-FC} is the objective function of perfect competition condition that is calculated by LMO. As previously mentioned, LMO in accordance with [26,29] that VPPs forming the collusive group participate in the market as a single integrated entity to achieve Z_{LMO}^{DA}. Therefore, simulation problem of their market participation is solved based on this assumption.
Thus, LMO can detect the formation of capacity-withholding groups of VPPs and strategies using the proposed $DMCWI^{DA}$. In the second stage of the day-ahead market, he/she examines the impact of the risk index on the results obtained from the first stage.

2.3.3 Third stage of the day-ahead market optimization problem

In the third stage of the day-ahead market problem, LMO attempts to modify the network configuration in an effort to reduce the market power of withholding groups. Thus, the objective function of this stage can be presented as Eq. (17):

$$\underset{\Psi}{Min}\ Z_{LMO}^{DA} = \quad (17)$$

$$\sum_{\psi\in\Psi}\sum_{\omega\in\Omega^{\omega}} \pi_{\omega}\zeta_{\omega} + \beta\cdot[\rho - \frac{1}{1-\alpha}\sum_{\omega\in\Omega^{\omega}}\pi_{\omega}\mu_{\omega}]$$

Where, Ψ is the set of feasible topologies of the distribution system that the operating constraints of the system are satisfied. The model adopted in this paper follows the framework established in [30].

3. Solution methodology

The flowchart of the proposed algorithm is presented in Fig. 2. As shown in Fig. 2, the LMO generates scenarios for the day-ahead system's load, market prices (from VPPs' viewpoints), and intermittent electricity generation facilities. Then, LMO reduces the generated scenarios for the described uncertainties. LMO receives the VPPs' bids/offers. Hence, LMO simulates the day-ahead full-competition market problem using the proposed formulation of the first stage considering the no-capacity withholding process. The LMO utilizes the PBUC process for different market scenarios from VPPs' viewpoints for the no-capacity withholding process. Based on Fig. 2, the LMO should estimate all of the capacity-withholding groups and solve the first stage problem considering the capacity-withholding groups. The LMO performs the PBUC simulation procedure for different market scenarios from VPPs' viewpoints for the capacity withholding group formation. In the second stage of the day-ahead market problem, the LMO solves the proposed optimization process of the second stage of the second-level problem; and finds all cases of dynamic capacity-withholding that result in a reduction in social welfare. Then, he/she calculates $DMCWI^{DA}$ by comparing the obtained results with the conditions of perfect competition. The LMO determines the optimal scheduling of VPPs and his/her distributed energy resources and declares the volume of electricity generation of VPPs for the day-ahead horizon.
The proposed three-stage optimization problem of each market problem is a Mixed-Integer Linear Programming (MILP) optimization problem with the following methods:

- The Monte Carlo method was utilized to generate scenarios for loads and prices. Furthermore, this technique was employed to forecast the LMO's intermittent electricity generation, charge/discharge, and renewable units of VPPs [31].
- Multiple scenarios were generated and reduced using Ref. [31] and the scenario tree was used for stochastic optimization.
- The proposed model was solved by the CPLEX solver of GAMS.

- The simulation was carried out on a laptop (11th Gen Intel, Core i7-1165G7, 2.80 GHz, 2803 MHz, 4 Cores, and 16 GB RAM).
- The total computational time in the stated algorithm in the article is 4 minutes and 48 seconds.

4. Simulation results

The proposed framework was assessed using the 123-bus test system. Fig. 3 depicts the topology of the test system. The information related to the network structure is considered according to Ref. [32]. As shown in Fig. 2, the studied distribution network includes five VPPs that participate in LEM. The reduced scenarios of the studied network are shown in Table I. Fig. 4 presents the estimated values of system loads for the day-ahead market horizon. As can be observed in Fig. 4, the total load is 1311.2 MW, while the average load is 54.63 MW. Additionally, the peak load and load factor are 67.2 MW and 81.3%, respectively. The distributed energy resources' parameters of VPPs are presented in Table II. In addition, the distributed energy resources' parameters of LMO are presented in Table III and Table IV.

The LMO performs the PBUC simulation procedure for different market scenarios from VPPs' viewpoints for the capacity withholding group formation. Fig. 5 presents the values of electricity market prices that were considered by the VPPs to perform the PBUC process. Fig. 6 presents the value of electricity generation of VPPs for the full-complete competition conditions.

Table I. Parameters of generation and reduction scenarios for the 123-bus system.

Scenario generations	Value
Number of PV system power generation	100
Number of wind turbine power generation	100
Number of day-ahead load and price	100
Number of PV reduced scenarios	4
Number of wind turbine reduced scenarios	4
Number of day-ahead load and price reduced scenarios	2

Fig. 7 depicts the estimated electricity generation of renewable units of LMO for different scenarios. According to Fig. 7, the LMO could provide part of the market's loads with these available resources. In addition, the solar radiation levels and wind speed data align with the data reported in Ref. [32].

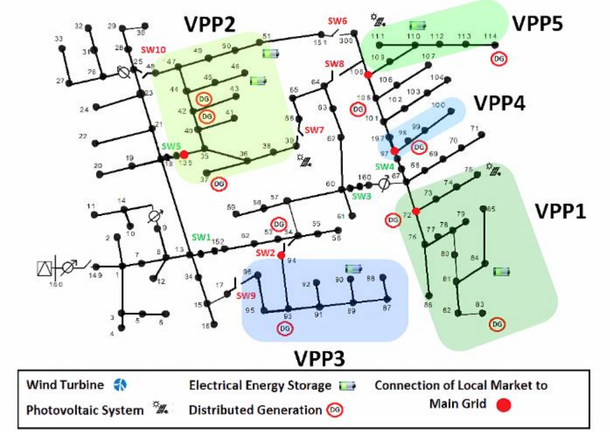

Fig. 3. The topology of the 123-bus test system.

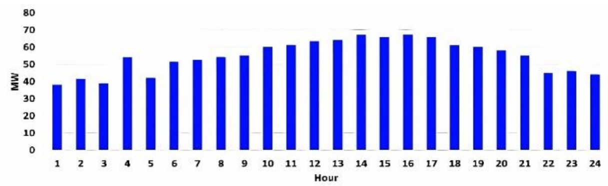

Fig. 4. The day-ahead load forecasting for the network.

Table II. The distributed energy resources of VPPs.

Non-intermittent Units Capacity	VPP1=20 MW, VPP2= 15,20 MW, VPP3=10 MW, VPP4=10 MW, VPP5=10 MW
(PV) Capacity	VPP1=5 MW, VPP2= 5 MW, VPP3=5 MW, VPP4=0 MW, VPP5=4 MW
(WT) Capacity	VPP1=7 MW, VPP2= 5 MW, VPP3=0 MW, VPP4=5 MW, VPP5=0 MW
(ESS) Capacity	VPP1=5 MW, VPP2= 4,5 MW, VPP3=4 MW, VPP4=4 MW, VPP5=4 MW
Non-intermittent Units Ramp-up	VPP1=10 MW/h, VPP2= 5,10 MW/h, VPP3=5 MW/h, VPP4=5 MW/h, VPP5=5 MW/h
Non-intermittent Units Ramp-down	VPP1=10 MW/h, VPP2= 5,10 MW/h, VPP3=5 MW/h, VPP4=5 MW/h, VPP5=5 MW/h
Non-intermittent Units fix cost	VPP1=10$/MWh, VPP2=25$/MWh, VPP3=15$/MWh, VPP4=20$/MWh, VPP5=20$/MWh
Non-intermittent Units variable cost	VPP1=35$/MWh, VPP2=45$/MWh, VPP3=30$/MWh, VPP4=30$/MWh, VPP5=35$/MWh

Table V presents the probable combination of capacity-withholding groups and their corresponding identification number. Fig. 8 displays the results related to creating a collusive group between VPP2 and VPP5.

Table III. The distributed energy resources of LMO.

Type of Units	Capacity (MW)	Connected Bus
Conventional generation units	2 MW, 3 MW	52, 63
PV system	1 MW, 1 MW	22, 13
Wind turbines	1 MW, 1 MW	58, 6
EES	1 MW, 2 MW	27, 20

Table IV. Characteristics of Conventional generation units of LMO.

Ramp-up (MW/h)	Ramp-down (MW/h)	Fix cost $/MWh	Variable cost $/MWh
0.5,0.5	0.5,0.5	15, 20	30,35

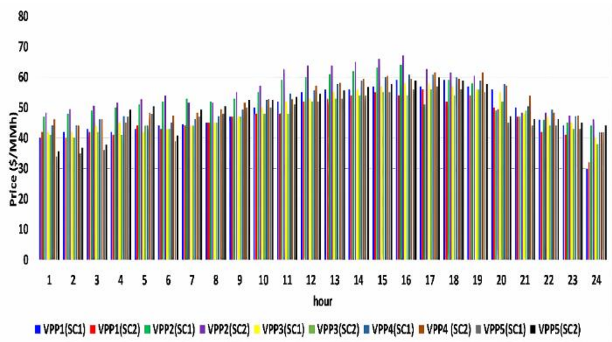

Fig.5. Prices of VPPs in the day-ahead market horizon.

As shown in Fig. 8, the preference of VPP5 is to reduce its capacity compared to the conditions of perfect competition. The total power that can be provided by VPP5 after the formation of a group with VPP2 for dynamic capacity withholding decreases by about 32.67%. This reduction in capacity is done with the aim of influencing the market conditions to increase the market share of VPP 2. Fig. 9 depicts the estimated values of $DMCWI^{DA}$ for the day-ahead market horizon. In this stage, the impact of risk on the index values is not taken into account, and the risk index is equal to zero. As shown in Fig. 9, the average and maximum values of $DMCWI^{DA}$ are 0.25 and 0.713, respectively. The 24th dynamic capacity-withholding group corresponds to the coordinated bidding of all VPPs for the day-ahead horizon that leads to the maximum capacity withholding of these entities. Then the operator performs the sensitivity analysis and determines the risk index on the results of stage 2.

The change in the risk index weight coefficient in Fig. 10 for the results of the group consisting of VPP 2, VPP3, and VPP5 shows the growth of the $DMCWI^{DA}$ index. Thus, the average $DMCWI^{DA}$ index increases from 27.86% for $\beta=0$ to 32.88% for $\beta=1$.

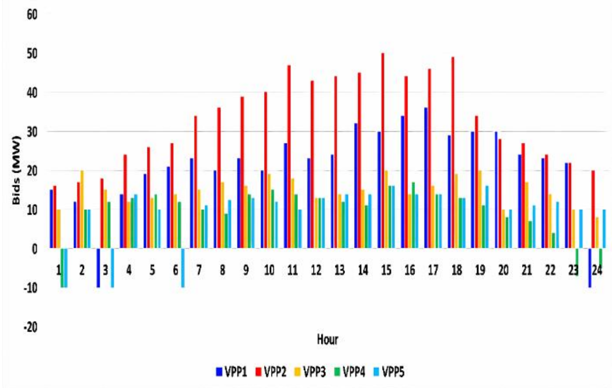

Fig. 6. The VPPs' bids in full-competition condition in the day-ahead market.

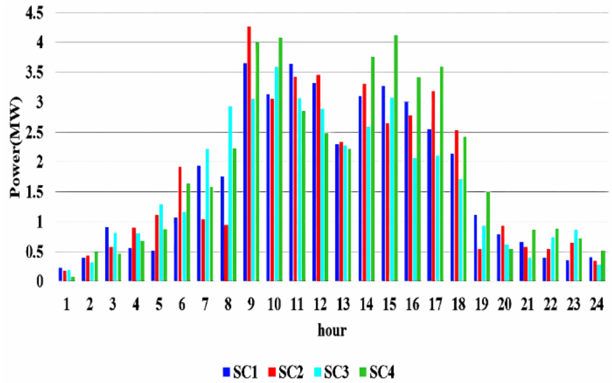

Fig. 7. The estimated value of day-ahead horizon for renewable resources of LMO.

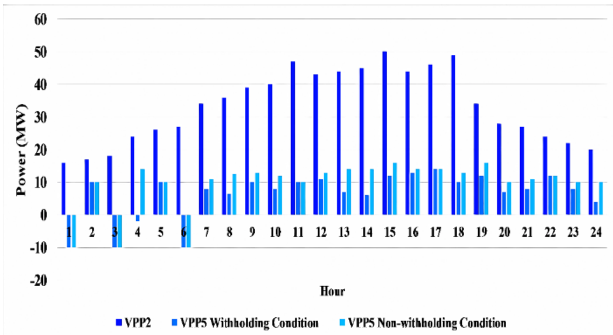

Fig. 8. Strategies of VPP5 & VPP2 as a collusive group.

Fig. 11 displays the average changes of $DMCWI^{DA}$ for the change of the risk index in the day-ahead market horizon. The results show that with the increase of the system's risk aversion index, the values of $DMCWI^{DA}$ increase for all possible modes of group formation. For example, in Group 24, this increase reaches up to 32.5%.

In the third stage of the day-ahead market problem, the operator attempts to reduce the market power of withholding groups by modifying the network topology.

Due to network constraints, market participants who are not in the capacity-withholding groups cannot have a proper impact on the market outcomes. By changing the network configuration through changes to the status of the tie switches, LMO can increase the likelihood of these units having a proper impact on the market outcomes. Table VI. presents the status of network tie switches.

In all cases where VPP2 is part of a withholding group, the $DMCWI^{DA}$ decreases when the market operator selects the first network configuration. As shown in Fig. 12, the value of the day-ahead market capacity-withholding index decreases for groups 1, 6, 7, 12, 13, and 22, orderly during the network peak hours from 12:00 to 14:00 as a result of change in the network configuration.

Table V. The withholding groups

Groups	Withholding groups	Groups	Withholding groups
1	VPP1-VPP2	13	VPP1-VPP2-VPP5
2	VPP1-VPP3	14	VPP1-VPP3-VPP4
3	VPP1-VPP4	15	VPP1-VPP3-VPP5
4	VPP1-VPP5	16	VPP1-VPP4-VPP5
5	VPP2-VPP3	17	VPP2-VPP3-VPP4
6	VPP2-VPP4	18	VPP2-VPP3-VPP5
7	VPP2-VPP5	19	VPP3-VPP4-VPP5
8	VPP3-VPP4	20	VPP1-VPP2-VPP3-VPP4
9	VPP3-VPP5	21	VPP1-VPP2-VPP3-VPP5
10	VPP4-VPP5	22	VPP1-VPP2-VPP4-VPP5
11	VPP1-VPP2-VPP3	23	VPP2-VPP3-VPP4-VPP5
12	VPP1-VPP2-VPP4	24	VPP1-VPP2-VPP3-VPP4-VPP5

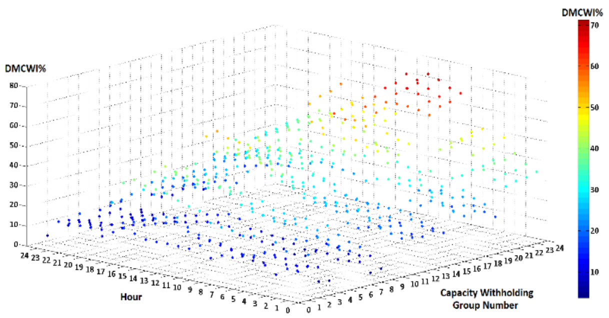

Fig. 9. The calculated values of $DMCWI^{DA}$.

The market power of VPP2 across buses 1 to 30 decreases by changing the location of injection power by VPP3, which is not part of the mentioned withholding groups. As a result, the average value of $DMCWI^{DA}$ in these groups decreased from 34.2% to 30.0%. By changing the network configuration from the initial configuration to the second configuration, the outcomes of the market will be improved. It is possible to use the capacity of the VPP2 while it is not present in the capacity-withholding groups.

By changing the network configuration to the second configuration. If groups 3, 8, 9, 10, 14, 15, 16, and 19 withhold capacity, it will lead to an increase in costs in the market. By utilizing configuration 2 of the network structure and injecting power through VPP2 on the right side of the network, the LMO can reduce the market power of capacity-withholding groups.

Table VI. The status of network tie switches.

# Switch	Co-base	Co-1	Co-2	Co-3
1	on	on	on	on
2	on	off	off	off
3	on	on	on	on
4	on	on	on	off
5	on	on	on	on
6	off	off	off	on
7	off	off	on	on
8	off	off	on	on
9	off	on	on	on
10	off	off	off	off

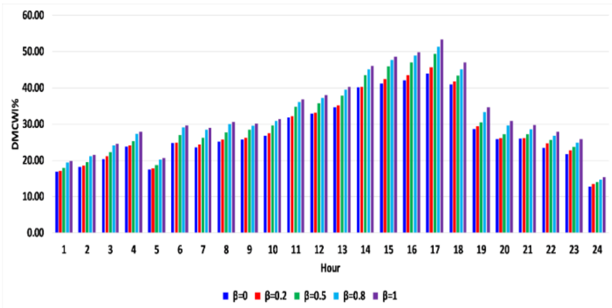

Fig.10. Changes in the $DMCWI^{DA}$ index of VPP 2, VPP 3, and VPP 5 due to the change in the risk index.

According to Fig. 13, the average values of the $DMCWI^{DA}$ in these 3 hours and for the specified groups have decreased from 30.3% to 27.3% in configuration 2 based on the fact that the VPP2 competes with the capacity-withholding groups.

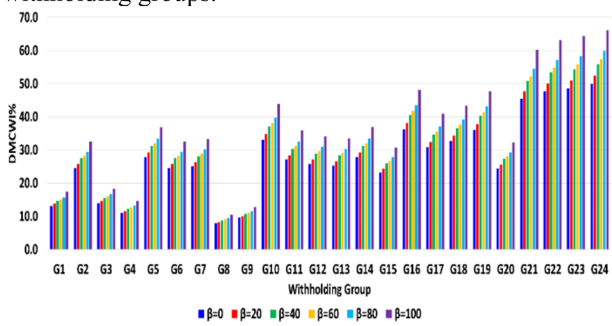

Fig. 11. The average changes of $DMCWI^{DA}$ index per change of risk index.

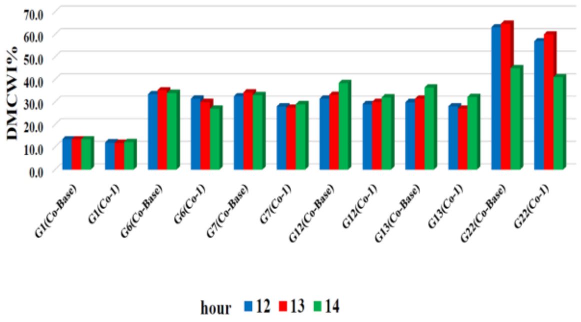

Fig. 12. The effect of configuration 1 on $DMCWI^{DA}$.

When LMO chooses the third configuration, the market power of groups 2, 3, 8, and 14 is mitigated. This is due to the fact that VPP2, which was not included in the previously described capacity-withholding groups, can inject power on both sides of the network, mitigating the impact of capacity-withholding by other VPPs. In other words, by enabling power injection for virtual power plants 2 and 5 on the right side of the network, the level of competition in LEM in this section of the network will increase. Fig. 14 shows that the competition increase due to a change in the network configuration decreases the average value of $DMCWI^{DA}$ for the specified withholding groups from 24.7% to 21.5%.

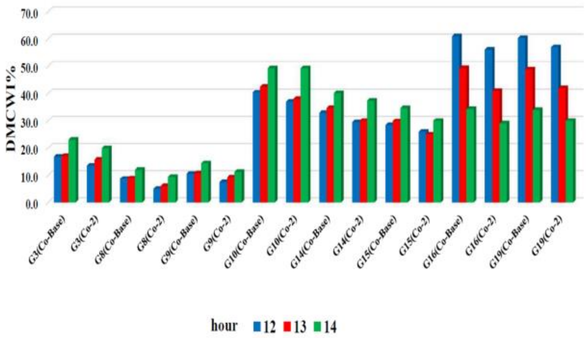

Fig. 13. The effect of configuration 2 on $DMCWI^{DA}$.

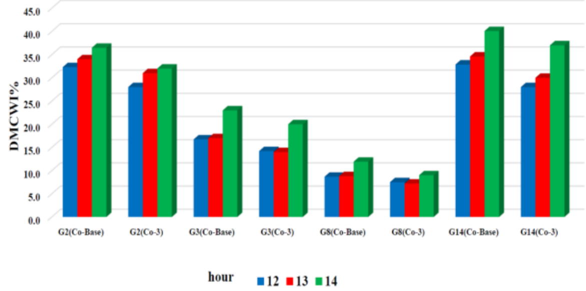

Fig. 14. The effect of configuration 3 on $DMCWI^{DA}$.

Fig. 15 indicates that by selecting configuration 4, LMO reduces the average value of $DMCWI^{DA}$ for groups 2, 3, 4, 10, 14, and 16 from 32.5% to 28%. The reason behind this decrease in the index value is the change in the network structure, which increases competition on the central and right sides of the network. The operator reduces the market power of capacity-withholding groups by allowing power injection from the VPPs that are not part of these groups.

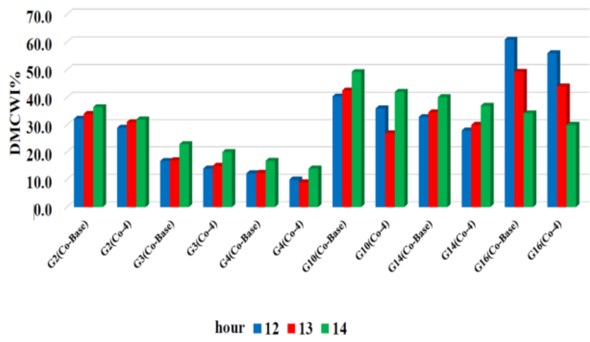

Fig. 15. The effect of configuration 4 on $DMCWI^{DA}$.

5. Conclusion

This paper investigated a mixed-integer linear optimization algorithm for the day-ahead optimal scheduling of virtual power plants (VPPs) in the local electricity market. The analysis of a 123-bus network revealed the possibility of strategic capacity withholding. The results showed that dynamic capacity withholding increased the average cost of the system by 25% in the day-ahead. It should be noted that the risk-averse behavior of LMO influenced the enhancement of the market power of withholding groups. Studies demonstrated that, on average this behavior can lead to up 5.2% greater increase in the index under risk-averse conditions compared to risk-neutral case. The change in the network configuration influenced collusion outcomes in the market. The investigations revealed that shifting from the initial topology to the first topology led to a decline in the market power groups 1, 6, 7, 12, 13, and 22, reducing the index value from 32.4% to 30%. It was revealed that enhancing competition on different sides of the network through topology modification could lead to a reduction in the average values of $DMCWI^{DA}$ by approximately 5%.

6. References

[1] M.Mokari, M.H.Moradi, Yan Bao "Fuzzy risk-based optimal reactive power dispatch in a wind-integrated power system". *Tabriz Journal of Electrical Engineering (TJEE)*, vol. 53, no. 1, Spring 2023.

[2] R. Sharikabadi, A. Abdollahi, M. Rashidinejad, M. Shafiee, "Probabilistic–Possibilistic modeling of V2G parking lot with the approach of improving flexibility in the Security-Constrained Unit Commitment". *Tabriz Journal of Electrical Engineering (TJEE)*, vol. 53, no. 3, Fall 2023.

[3] J.Shi, W.Zhang, Y.Bao, D.Gao, Senyong Fan, Zhihao Wang, "A risk-based procurement strategy for the charging station operator in electricity markets considering multiple uncertainties", *Electric Power System Research*, Vol. 241, 111381, 2025.

[4] M. Sheykhha, M. Setayesh Nazar," Dynamic capacity withholding assessment of virtual power plants in local energy and reserve market", *Sustainable Energy, Grids and Networks*, vol. 40, 101514, 2024.
[5] Bevink.K.C, A.Verma,"Decentralized local electricity market model using Automated Market Maker" *Applied Energy*, vol.334,120689, 2023.
[6] Hong. Q, Meng. F, Liu.J, Bo. R," A bilevel game-theoretic decision-making framework for strategic retailers in both local and wholesale electricity markets" *Applied Energy*, vol. 330, part A,2023.
[7] J.Song, W.Zheng, M.Chen, L.Qi,Q.Zou, "Analysis of collusive bidding characteristic in the power spot market based on multi-agent reinforcement learning simulation", *Springer journal of Electrical Engineering*, vol.107, no.4, 2025.
[8] S.Salarkheili, M. Setayesh Nazar, Wozbal.D, Jabari.F," Capacity withholding of GenCos in electricity market using security-constrained generation maintenance scheduling", *International Journal of Electrical Power & Energy Systems*, vol.146,108771 ,2023.
[9] M.Nikkhah, M Samadi, "An analytical approach for evaluating the collusion possibility between generation companies and transmission companies". *Electric Power Systems Research*, vol.217,109113,2023.
[10] B.Sun, S.Cheng, "Identification of Generators' Economic Withholding Behavior Based on a SCAD-Logit Model in Electricity Spot Market". *Energies*, vol.15, no.11, 4135,2022.
[11] Teng.Tu, Yi.D. "Collusion Potential Assessment in Electricity Markets Considering Generation Flexibility" *CSEE Journal of Power and Energy System*, vol.9, no.4 pp. 1551-1566,2023.
[12] P.Razm, M.Buygi," Collusion Strategy Investigation and Detection for Generation units in Electricity Market using Supervised Learning Paradigm" *IEEE Systems Journal*, vol.15, no.1 pp.146–157.
[13]M.Loschenbrand, M.Korpas, M.Fodstad, "Market power in hydrothermal systems with marginal cost bidding". 15th International Conference on the European Energy Market, Lodz, Poland, 2018.
[14] P.Dijkstra, M.Haana, M.Mulder, "Industry structure and collusion with uniform yardstick competition: theory and experiments". *International Journal of Industrial Organization*, vol.50, pp. 1-33, 2017.
[15] T.Durmaz, S.Acar, S.Kizilkaya, "Generation failures, strategic withholding, and capacity payments in the Turkish electricity market", *Energy Policy*, vol.184, 113897, 2024.
[16] Sun, B., Deng, R., Ren, B.: Identification method of market power abuse of generators based on lasso-logit model in spot market. *Energy 238*, 121634, 2022.
[17] X.Lin, T.Huang, E.Bompard, B.Wang,Y.Zheng, "Ex-ante market power evaluation and mitigation in day-ahead electricity market considering market maturity levels", *Energy*, vol.278, 127777, 2023.
[18] D.Aliabadi, M.Kaya, S.Güvenç, "Determining collusion opportunities in deregulated electricity markets". *Electric Power Systems Research*, vol.141, pp. 432–441, 2016.
[19] A.Sapio.A, N.Spagnolo, "Price regimes in an energy island: Tacit collusion vs. cost and network explanations". *Energy Economics*, vol.55, pp. 157-172, 2016.
[20] E.Baranes, M.Podesta, J.Poudou, "Mixed, bundling may hinder collusion". *Research in Economics*, vol.70, no.4, pp.638-658,2016.
[21] M.Shafie-khah, P.Siano, D.Fitiwi, S.Santos,J. Catalao, E.Heydarian-Forushani. "Regulatory support of wind power producers against strategic and collusive behavior of traditional thermal units". 13th International Conference on the European Energy Market (EEM), Porto, Portugal,2016.
[22] S.Ramyar.S, L.Lie, Y.Chen, "A Power Market Model in Presence of Strategic Prosumers". *IEEE Transactions Power Systems*, vol.35, no.2, pp.898-908, 2020.
[23] H.Guo, Q.Chen, X.Fang, K.Liu, Q.Xia, C.Kang, "Efficiency Loss for Variable Renewable Energy Incurred by Competition in Electricity Markets". *IEEE Transactions on Sustainable Energy*, vol.11, no.3, pp.1951-1964, 2020.
[24] G.Evangelos, C.Micheal," Withholding strategies for a traditional and wind generation portfolio in a joint energy and reserve pool market: A gaming-based approach", *Computers and chemical Engineering*, vol.134, pp.462–49,2020.
[25] M.Tabatabaei, M.Setayesh-Nazar,M.Shafie-khah,J. Catalao," An integrated framework for dynamic capacity-withholding assessment considering commitment strategies of generation companies", *Electrical Power and energy systems*, vol.134, 107321, 2022.
[26] M.Tabatabaei, M.Setayesh-Nazar,M.Shafie-khah,J. Catalao," Optimal scheduling of microgrid-based virtual power plants considering demand response and capacity withholding opportumities" Conference of IEEE Madrid power Tech,Madrid, Spain,2021.
[27] X.Lin, Y.Zheng, Z.Xiang, B.Wang"Optimal market-based battery energy storage system capacity sizing: Considering strategic behavior of collusions in the electricity day-ahead market", *Journal of Energy Storage*, vol.120, 116309,2025.
[28]L.Wang,Y.Zhang "Stochastic cooperative bidding strategy for multiple microgrids with peer-to-peer energy trading" *IEEE transactions on industrial informatics*, vol.18, no.13, pp.1447-1457, 2022.
[29] Lin.x, Huang.T, Wu.H, Bompard.E, Wang.Beibei "Market zone configuration under collusive bidding among the conventional generators and renewable energy sources in the day-ahead electricity market", *Electric Power Systems Research*, vol.232, 110373, 2024.
[30] G.Homgjun, Ma.W, X.Yingmeng, T.Zao, X.Xiangdong, P.Homgjin "Multi-objective Dynamic Reconfiguration for Urban Distribution Network Considering Multi-level Switching Modes", *Journal of Modern Power Systems and Clean Energy*, vol.10, no.5, pp.1441-1255, 2022.
[31] X.Guo, Z.Dong, R.Zhang, D.Hill, "Multi-time scale coordinated voltage/var control of high renewable-penetrated distribution system", *IEEE Transaction on Power System*, vol.32, no.6, pp.4398-4408, 2017.
[32] H.Zakernezhad, M.Setayesh-Nazar, M.Shafie-khah, J.Catalao," Optimal resilient operation of multi-carrier energy systems in electricity markets considering distributed energy resource aggregators", *Applied Energy*, vol.299,117271, 2021.

Nomenclature

Abbreviation

ADN	Active Distribution Network.
CVaR	Conditional Value at Risk.
Co	Configuration
DA	Day-Ahead.
DG	Distributed Generation.
DER	Distributed Energy Resource.
DA	Day-Ahead.
DER	Distributed Energy Resource.
DG	Distributed Generation.
DMCWI	Day-ahead Market Capacity -Withholding
ESS	Electrical Storage System.
LEM	Local Energy Market.
LMO	Local Market Operator.
MILP	Mix Integer Linear Programming.
PBUC	Price Based Unit Commitment.
VPP	Virtual Power Plant.
WT	Wind Turbine.

Parameters

B_{ℓ}	Susceptance of line.
$C_c^{C,F}$	Cost of non-intermittent power plant c [$/h].
$C_c^{C,V}$	Variable cost of non-intermittent power plant c [$/MWh].
$E_{st}^{S,\min}$	Lower bound of the energy stored in storage
$E_{st}^{S,\max}$	Upper bound of the energy stored in storage unit s in time period t [MWh].
$P_c^{C,\min}$	Minimum power generation of non-
$P_c^{C,\max}$	Maximum power generation of non-intermittent power plant c [MW].
$P_{dt\omega}^{D}$	Internal demand of VPPs for demand level d
$R_c^{C,D}$	Down ramping limit of non-intermittent
$R_c^{C,U}$	Up ramping limit of non-intermittent power plant c [MW/h].
U_{dt}^{D}	Utility of demand d acquired from the energy
α	Confidence level used to compute the CVaR.
β	Weighting parameter to model the trade-off between expected profit and CVaR.
Δt	Duration of time periods [h].
$\eta_s^{S,C}$	Charging efficiency of storage unit s [%].
$\eta_s^{S,D}$	Discharging efficiency of storage unit s [%].
$P_{\ell}^{L,\min}$	Lower bound of the Power flow in line.
$P_{\ell}^{L,\max}$	Upper bound of the Power flow in line.
$G_g^{G,F}$	Fixed cost of non-intermittent power plant of
$G_g^{G,V}$	Variable cost of non-intermittent power plant
$\lambda_{t\omega}^{DA}$	DA energy market price in time period t
$\lambda_{t\omega i}^{DA}$	DA offer price of VPP i-th in time period t
$U_{rt}^{R,LMO}$	Operation cost of renewable units belong to LMO in time period t [$/MWh].

Indexes

c	Non-intermittent power plant index.
d	Demands index.
i	Index of VPP.
ℓ	Network line index.
n	Network node index.
r	Renewable generating unit index.
$r(\ell)$	Receiving-end node of network line.
s	Storage unit index.
$s(\ell)$	Transferring-end node of network line index.
t	Time period index.
g	Units belong to LMO index.
m	Node common coupling to network index.
ω	Scenario index.

Sets

Ω^C	The sets of non-intermittent power plants.
Ω^D	The sets of demands.
Ω^L	The sets of network lines.
Ω^M	The sets of network nodes connected to the
Ω^N	The sets of network nodes.
Ω^R	The sets of stochastic renewable generating
Ω^S	The sets of storage units.
Ω^T	The sets of time periods.

Ω^{ω}	The sets of scenarios.

Variables

$e_{st\omega}^{S}$	Energy stored in storage unit s for time period
$p_{ct\omega}^{C}$	Power generation of non-intermittent power
p_{t}^{DA}	Power traded in the DA energy market in time period t [MW].