Scientia Iranica D (2019) 26(6), 3622–3634

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions D: Computer Science & Engineering and Electrical Engineering
http://scientiairanica.sharif.edu

Invited Paper

Micro-grids bidding strategy in a transactive energy market

H. Nezamabadi and V. Vahidinasab*

Department of Electrical Engineering, Abbaspour School of Engineering, Shahid Beheshti University, Tehran, Iran.

Received 31 July 2019; accepted 16 September 2019

KEYWORDS
Bidding strategy;
Smart contract;
Energy blockchain;
Transactive Energy Market (TEM);
Micro-Grids (MGs);
Bi-level optimization;
Uncertainty;
Interval coefficient modelling.

Abstract. This paper proposes Micro-Grid (MG) bidding strategy in the Transactive Energy Market (TEM) in which market participants are able to negotiate and trade by a new Smart Contract (SC) in a peer-to-peer way. In such a market, MG can balance its deviations as a result of the intermittency of the renewable energy sources and the volatility of the load. The uncertainty was handled by interval optimization. By participation in the TEM, the MG bidding problem was a bi-level optimization with interval coefficient, in which the profit of the MG was maximized in the upper level and the behaviour of the rivals in the TEM was modelled in the lower level. In order to solve the aforementioned problem, the proposed model was recast as a single-level interval optimization problem by the Karush-Kuhn-Tucker (KKT) conditions and the interval optimization concept. Simulation results showed the applicability of the proposed model and 1.7% increase in the profit of the MG for a 4-hour-duration-basis TEM.

1. Introduction

Due to the widespread use of intermittent Renewable Energy Sources (RESs), the emergence of new technologies, and extension of communication and control to the end-user, the power system landscape is undergoing significant changes [1]. Using the new technology, which is affected by the economic and control techniques, Transactive Energy System (TES) can balance the supply and demand via a value-based logic [2]. Regarding the operation of the power system, the passive distribution system moves toward an active one, in which Micro-Grids (MGs) can control the Distributed Energy Sources (DERs) [3]. From the economic aspect, the transactions are facilitated by the Smart Contracts (SCs) and blockchain technology under the TES paradigm for the procurement of imbalanced energy [4].

Under TES paradigm, the business models of the entities, which are active in the distribution sector, undergo extensive changes. By considering the traditional business model, the MGs can participate in the Day-Ahead Market (DAM). Due to the uncertainties in the forecast of RESs production and loads consumption, they are forced to deal with imbalances in the Real-Time Market (RTM) [3]. However, by the emerging transactive MG controller, the MG can overcome the uncertainties in Transactive Energy Market (TEM) rather than RTM, whose prices are unfavourable in comparison with the DAM [5].

A distributed TEM is envisioned to integrate multiple entities located mainly at the distribution level so that active distribution customers (i.e., consumers and prosumers) can buy and sell their energy without involving any third party (e.g., peer-to-peer contracts) by the decentralized pricing mechanisms [6]. Some technical issues of energy transaction (e.g., loss allo-

*. *Corresponding author.*
E-mail address: v_vahidinasab@sbu.ac.ir (V. Vahidinasab)

doi: 10.24200/sci.2019.54148.3616

cation) inside the MGs were considered by DiSilvestre et al. [7]. The loss allocation methods, which were appropriate for the peer-to-peer trades, were proposed by Nikolaidis et al. [6]. The application of blockchain technology to the MGs without the requirement of central intermediaries was also proposed by DiSilvestre et al. [7]. In this study, the energy blockchain included power losses and the assignment of losses to each energy transaction (i.e., each block) in the MG was done by the Independent System Operator (ISO).

On the other hand, the second sets of studies focus on the consensus algorithm and market design for the market participants [8]. In the self-managed decentralized TEM, any requirement for an intermediary between two parties is resolved by the blockchain technology, which is basically used for tracking economic transactions without the need for a trusted intermediary institution (e.g., a bank). Therefore, the energy blockchain, in which the management of transactions is decentralized, can be applied as a decentralized pricing mechanism [9].

Hence, the bidding problem of MGs in TEM is one of the main challenges faced by the MG manager. With the above-mentioned considerations, the objectives of this paper are to propose the bidding strategy of an MG as a transactive agent and to present the TEM framework, in which the MG can deal with the uncertainty of RESs production and load consumption.

The main contributions of this paper can be summarized into the following 3 main aspects:

1. In comparison with the previous studies, which investigate the technical issues of TEM and the market design, in this paper, the bidding strategy of the MG in the TEM is proposed by a bi-level optimization with interval coefficient, in which the profit of the MG is maximized in the upper level and clearing of the TEM is considered as the lower-level problem. In order to solve the proposed model, the problem is considered as a single-level interval optimization by using KKT conditions and interval optimization concept;
2. A two-price settlement mechanism is proposed to facilitate the participation of the MG in the TEM. Also, a proper SC is designed for the negotiation process of the MG with the rivals (e.g., aggregators);
3. Simulation results for an illustrative MG with 4 controllable DGs, 4 stochastic producers, one Energy Storage System (ESS), and one DR show that the MG tends to buy energy more expensive than the DAM price in the TEM instead of buying energy in RTM prices, which are the highest. Also, the MG tends to sell energy cheaper than the DAM price in the TEM instead of selling energy in RTM prices, which are the lowest. In the analysis of the profitability of the TEM for the MG, it is observed that the MG can earn 1.7% more profit in every 4 hours by the participation in the TEM. Consequently, in 24 hours of participation in TEM, it can increase its profit by 10.2%.

The remainder of this paper is organized as follows. Section 2 presents the transactive MG and the necessary layers for the formation of a transactive MG, the transaction evolution, the TEM structure, and the new designed SC. In Section 3, the proposed model is described. In Section 4, the model formulation and the mathematical subjects are explored. The numerical results are provided in Section 5. Finally, the results of the proposed model are concluded in Section 6.

2. Transactive MG

2.1. *Elements of transactive MG*

In Figure 1, the necessary layers for the formation of a transactive MG are shown. The first layer is the physical one. In the physical layer, there are sets of DERs, including RESs, Distributed Generations (DGs), ESSs, and Demand Responses (DRs). As the first necessity for the TES, the MG should be visible, controllable, and flexible. In order to achieve visibility, controllability, and flexibility, the components of MG should be equipped with sensors and controller in the technical layer. The technical layer includes all the electrical and mechanical equipment, which makes the MG system visible and controllable. The network layer is an interface between the technical layer and the business layer. It should receive the command of the MG manager and send the command to the technical layer. Also, it receives the real-time operation characteristics (i.e., production, consumption rate, etc.) and sends them to the MG manager for the decision-making process. In the business layer, the process of decision-making is done by the MG manager and its mathematical facilities. After interaction with the market layer, the market bidding strategy of the MG is determined in the business layer. In this layer, scheduling of the DERs is performed by the algorithms and the procedures, which are determined by the MG manager. Finally, in the market layer, the marketplace rules are determined by the structure of the market (i.e., payment rules, time scheduling rules, etc.). In the following, the evolution of transactions and the market structure are given.

2.2. *Evolution of transactions*

Traditional transaction models rely on a central authority to play the ISO role. In order to operate the grid in a secure and efficient manner, verifying and clearing of the transactions are granted to the central authority (i.e., ISO) on behalf of the market participants (i.e., MGs, storages, prosumers). In other words, the ISO

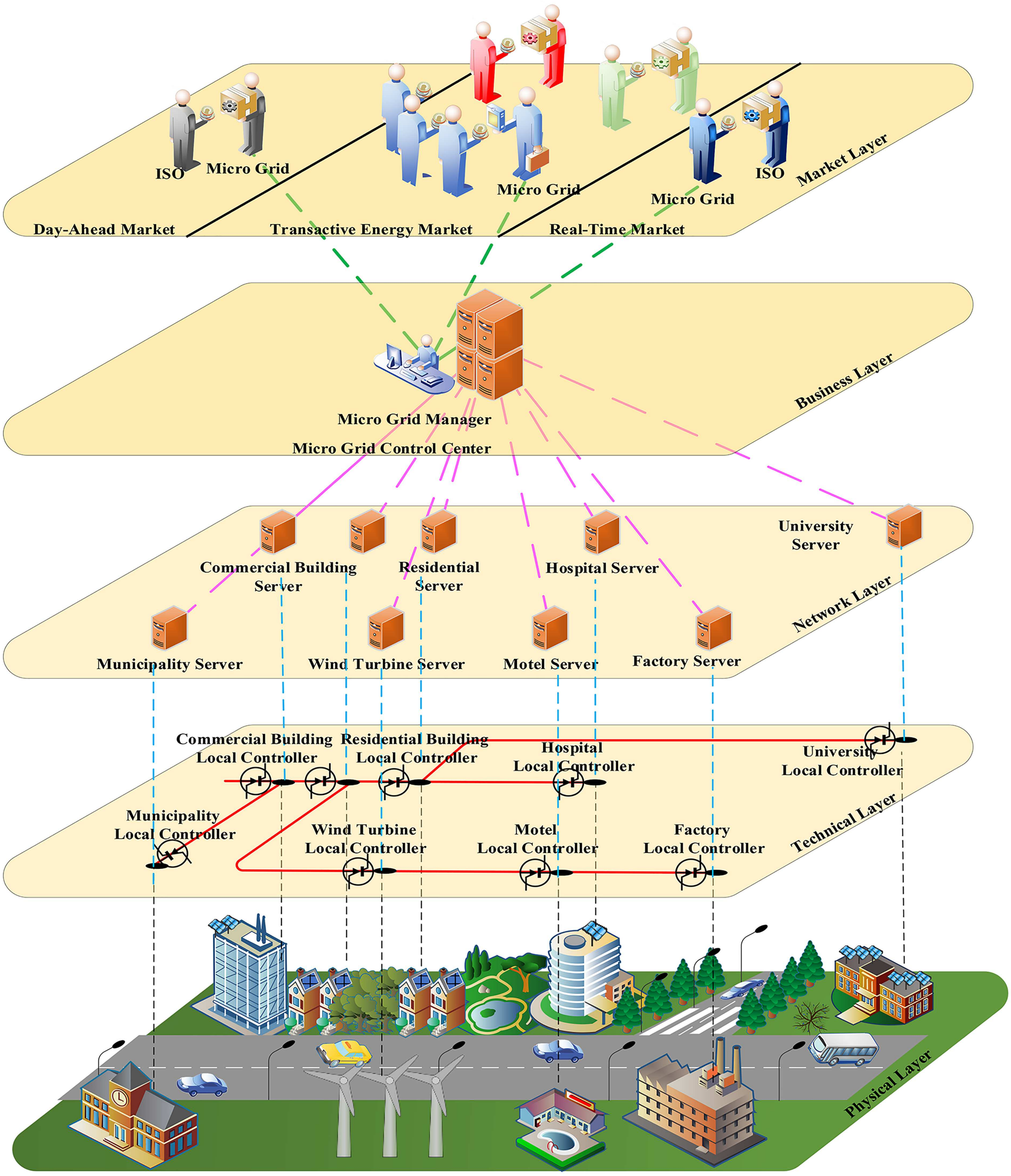

Figure 1. Transactive MG elements.

schedules all of the market participants in a centralized manner, which is called the pool market.

Under the TE paradigm, new transaction models have been suggested by enabling peer-to-peer and Smart Contracts (SCs) between transactive agents at the distribution level. The SC is a set of logic rules in the form of a coded script, which can be embedded into the blockchain to govern a transaction. In the blockchain technology, pools of recent transactions are ordered into a block. Then, the block is cryptographically linked to a chain of blocks (the blockchain) and verified by the consensus process - the process for determining what blocks get added to the chain [10]. In the consensus process, the access permission to the transactions data can be granted to everyone/permitted participants in the public/private blockchain. Although all of the participants are permitted to read and write data in the public blockchain,

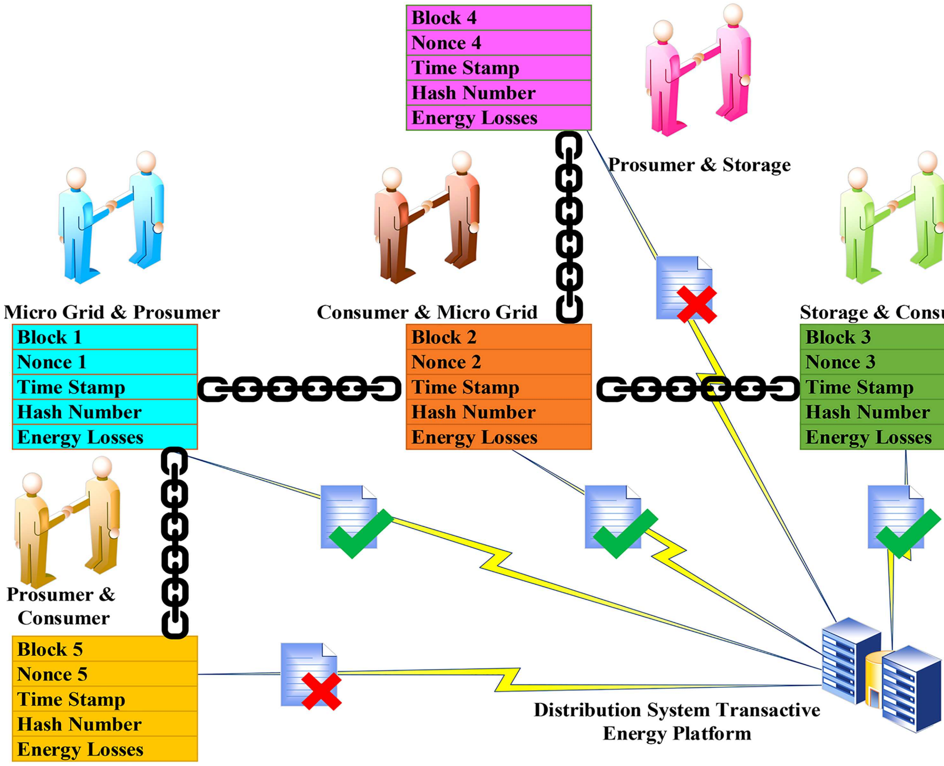

Figure 2. Energy blockchain.

only permitted participants can read and write data in the private one. By the private blockchain, ISO can guarantee secure and efficient operation of the grid. Based on the rules of the consensus model, each participant (i.e., MGs, prosumers, storages, etc.) broadcasts changes by forming new blocks and requesting validation. Once validated by the TE distribution system platform, the block is added to everyone's chain. In Figure 2, it is shown that active agents in the distribution system (i.e., MGs, storages, prosumers, and consumers) can sign SC with each other under the private blockchain technology. Since the signing SC is a complicating task and needs electrical and economical knowledge, aggregators can be allowed to sign the SC instead of their customers.

2.3. TEM design

Regarding the uncertainties of RES production and load consumption, the uncertainty level ranges from one day before at fully uncertain level to near the real time at a certain level. Currently, the producers/consumers should offer/bid their fully uncertain production/consumption to the DAM. The commitments of the producers/consumers are determined after the clearing of the DAM. They should balance their deviation from the DAM commitments in the RTM [5]. However, by decreasing the production uncertainty, there is an opportunity for the stochastic producers and consumers to interact with each other and balance their deviation by the TEM before the clearing of the RTM. In this paper, a three-stage market, which is sequentially implemented, is proposed. To prevent the arbitrage opportunity, the two-price settlement mechanism is considered in the markets. In the two-price settlement, the deviations from stochastic producers are settled at the less favourable Market Clearing Price (MCP) [5]. Such a pricing scheme is common in the settlements of European markets. Eq. (1) shows the relation of the MCPs of the DAM, TEM, and RTM.

$$\begin{cases} \lambda^{\mathrm{DAM}} \leq \lambda^{\mathrm{TEM}} \leq \lambda^{\mathrm{RTM}} & \text{for buyer} \\ \lambda^{\mathrm{RTM}} \leq \lambda^{\mathrm{TEM}} \leq \lambda^{\mathrm{DAM}} & \text{for seller} \end{cases} \tag{1}$$

The MCPs of the DAM and RTM make the price floor and cap for the buyer (i.e., $\lambda^{\mathrm{TEM}} \in [\lambda^{\mathrm{DAM}}, \lambda^{\mathrm{RTM}}]$) and the seller (i.e., $\lambda^{\mathrm{TEM}} \in [\lambda^{\mathrm{RTM}}, \lambda^{\mathrm{DAM}}]$), respectively. Thus, by moving from DAM to RTM, the favourability of the MCP is decreased for the stochastic sellers and buyers.

In Figure 3, the production levels of two stochastic producers and their cumulative commitments in the markets are illustrated. By the available information and the forecast values, both producers decide to offer the values A and B, which are fully uncertain, to the DAM (see Figure 3(a)). It is assumed that A and B are accepted in the DAM. Therefore, producers 1 and 2 are paid by the MCP of DAM (i.e. λ^{DAM}) after the clearing process.

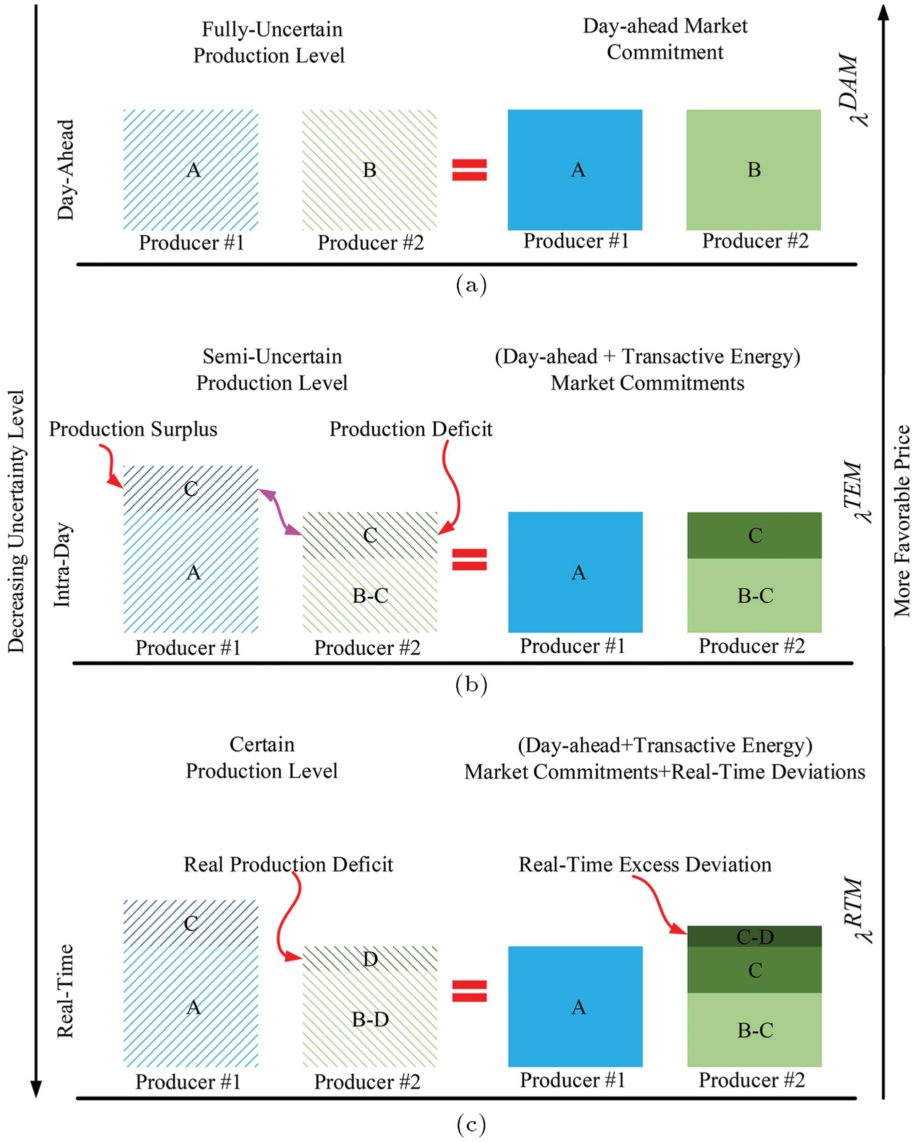

Figure 3. Energy transactions and commitments in the markets: (a) Day-Ahead Market (DAM), (b) Transactive Energy Market (TEM), and (c) real-time market.

By increasing the available information as time passes, the forecasts become more accurate at the TEM stage. In Figure 3(b), it is shown that Producer 1/Producer 2 underestimates/overestimates the production value as much as C. Both of the producers decide to offer the value C, which is semi-uncertain, to the TEM. Therefore, there is an opportunity for Producer 1 and Producer 2 to balance their deviation C with a more favourable price than that of the RTM by a peer-to-peer transaction.

Finally, the real-time stage is illustrated in Figure 3(c). In the real time, Producer 1 generates energy as much as the forecasted value in the TEM (i.e., $A + C$). Therefore, there is no need to balance any deviation. The real production deficit of Producer 2 is equal to D, which is less than C. Thus, producer 2 has to sell its excess production (i.e., $C - D$) by the least favourable price in the RTM. In this paper, the clearing process of the TEM is implemented every 4 hours in a day. Therefore, it can be implemented 6 times in a day.

2.4. Designing smart contract in the TEM

The SC of energy transaction should cover the scenario for buying and selling energy, which requires ISO validation. Sellers can list their flexibilities in energy consumption or production by instantiating an energy transaction SC. Buyers can make offers by taking action on the SC and ISO can take actions to validate the energy transaction. Once the buyer and the seller validate the trade, they will confirm the transaction again before the contract is agreed.

There are three participants in the SC. Players can take various actions. The logic written in the SC

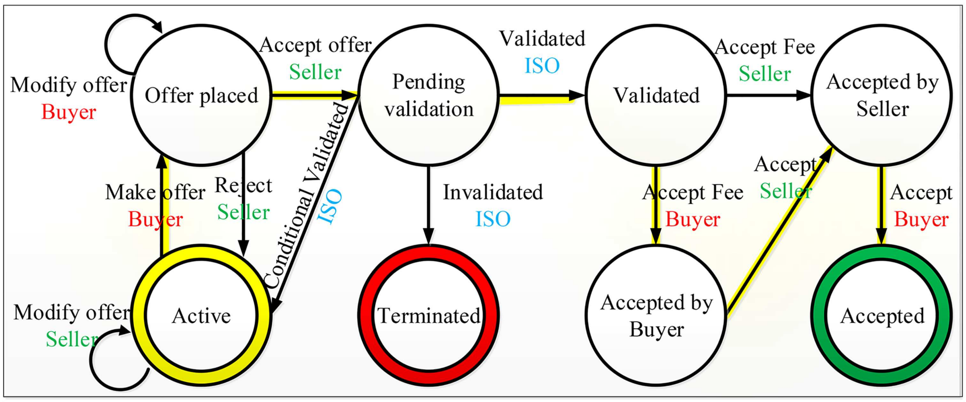

Figure 4. State transition diagram of the smart contract.

will modify the state, based on which actions are taken. The application roles in the SC are the following:

- **Seller:** An energy consumer/producer who consumes/produces energy less/more than its scheduled value and wants to sell its excess energy;
- **Buyer:** An energy consumer/producer who consumes/produces energy more/less than its scheduled value and wants to buy its deficit energy;
- **ISO:** An entity that validates energy transaction through security and allocates the side fees of the energy transaction between the seller and the buyer.

In Figure 4, the state transition diagram shows the possible flows and various transition functions at each state. Each user is allowed to take only certain actions depending on the application role. The happy (i.e., yellow shaded) path shown in the transition diagram traces a seller making an item available, a buyer making an offer, the ISO validating the energy transaction, and finally the seller accepting the offer.

2.5. MG business model under transactive energy paradigm

In the previous business models. the MG could participate in the DAM and then, it could balance its deviations from the RTM [3,11]. In a business plan, the MG can determine to sign an SC with load aggregators, i.e., other MGs for energy procurement by using blockchain technology. Therefore, between DAM and RTM, the MG can procure the energy deviation from the TEM.

3. Model description

3.1. Uncertainty characterization and interval optimization

Since the net load and RTM prices are so volatile, interval prediction is employed in this paper. In the prediction of intervals, it is common to forecast the central intervals of the uncertain parameter with a nominal coverage rate of $\gamma\%$ [5]. The main advantage of the interval prediction is that it can give users forecasts with a feeling of the level of forecast uncertainty for the upcoming period. In comparison with scenario forecasting, there is no need for extracting probability distribution function, which is a difficult statistical task. Therefore, the intervals of the net load and RTM prices are determined by a Central Forecast (CF) and a coverage rate, which defines the Lower Bound (LB) and Upper Bound (UB) of the prediction interval.

By the application of the interval prediction, interval optimization is employed to determine the bidding strategy of the MG in the TEM. In the interval optimization, the main problem is reaching the optimum value of the Objective Function (OF) by considering the interval parameter, which can be in the OF or in the constraints. This optimum value may be the worst or the best possible optimal solution. Net load is a parameter that directly affects the security and reliability of the MG. Hence, the worst case of the net load should be considered in real time to guarantee the security of the MG [3]. On the other hand, high volatility makes the RTM price forecast impossible. Therefore, the MG considers the worst case of the RTM prices to prevent unintentional losses.

3.2. Bidding strategy of MG in the TEM

Regarding the designed SC in Section 2.4, the MG can participate in a new market place, which is called TEM, and balance its deviation from DAM commitments. In the bidding strategy of MG in the TEM, it faces a two-stage decision-making problem. At the first stage, the MG bids in the TEM, whose structure is given in Section 2.3. To achieve the best bidding strategy in the TEM, the MG should compete with its rivals at this stage. It should model the behavior of its rivals. Therefore, the clearing of the TEM is the main problem of the MG at this stage. Then, after clearing the TEM, it should balance its real-time deviation by the RTM prices at the second stage.

4. Model formulation

4.1. Bi-level optimization with interval coefficient

In the proposed model, the MG should maximize the profit. In the following, the mathematical model of the bidding problem of the MG in TEM is given:

$$\underbrace{\text{Maximize Profit}}_{\substack{\alpha_t^{\text{TEM-sell}},\alpha_t^{\text{TEM-buy}},P_{d,t}^{\text{DR}},\\ P_{dg,t}^{\text{DG}},P_{str,t}^{ch},P_{str,t}^{dch},P_t^{\text{RT}}}} = \sum_{t\in T}\lambda_t^{\text{TEM-sell}}P_t^{\text{TEM-sell}} - \lambda_t^{\text{TEM-buy}}P_t^{\text{TEM-buy}} + \sum_{t\in T}\Bigg(\sum_{d\in S_{\text{FD}}}\rho_t^R\left[D_{d,t}^{\text{LB}},D_{d,t}^{\text{UB}}\right] + \sum_{d\in S_{\text{DR}}}C_{dr}P_{d,t}^{\text{DR}} - \sum_{dg\in S_{\text{DG}}}C_{dg}P_{dg,t}^{\text{DG}} - \sum_{str\in S_{\text{STR}}}C_{str}\left(P_{str,t}^{ch}+P_{str,t}^{dch}\right) - \left[\lambda_t^{\text{RTM-LB}},\lambda_t^{\text{RTM-UB}}\right]P_t^{\text{RT}}\Bigg). \tag{2}$$

Subject to:

$$\sum_{dg\in S_{\text{DG}}}P_{dg,t}^{\text{DG}} + \sum_{str\in S_{\text{STR}}}\left(P_{str,t}^{dch}-P_{str,t}^{ch}\right) - \sum_{d\in S_{\text{DR}}}P_{d,t}^{\text{DR}} = \sum_{d\in S_{\text{FD}}}\left[D_{d,t}^{\text{LB}},D_{d,t}^{\text{UB}}\right] + P_t^{\text{DAM}} + \left(P_t^{\text{TEM-buy}} - P_t^{\text{TEM-sell}}\right) + P_t^{\text{RTM}}, \quad \forall\ t, \tag{3}$$

$$P_{dg,t}^{\text{DG}}=P_{dg}^{\text{DG-init}} \qquad \forall\ dg, t=0, \tag{4}$$

$$P_{dg}^{\text{DG-min}} \leq P_{\omega,dg,t}^{\text{DG}} \leq P_{dg}^{\text{DG-max}} \qquad \forall\ \omega, dg, \forall\ t, \tag{5}$$

$$\begin{Bmatrix} J_{dg,t}^{\text{DG}} - K_{dg,t}^{\text{DG}} = I_{dg,t}^{\text{DG}} - I_{dg,t-1}^{\text{DG}} \\ J_{dg,t}^{\text{DG}} + K_{dg,t}^{\text{DG}} \leq 1 \end{Bmatrix} \qquad \forall\ dg, t, \tag{6}$$

$$\sum_{l=1}^{\text{MUT}_{dg}^{\text{DG}}} I_{dg,t+1}^{\text{DG}} - 1 \geq \text{MUT}_{dg}^{\text{DG}}, \qquad \forall\ J_{dg,t}^{DG}=1, \quad \forall\ dg, t, \tag{7}$$

$$\sum_{l=1}^{\text{MDT}_{dg}^{\text{DG}}} 1 - I_{dg,t+1}^{\text{DG}} \geq \text{MDT}_{dg}^{\text{DG}}, \qquad \forall\ K_{dg,t}^{\text{DG}}=1, \quad \forall\ dg, t, \tag{8}$$

$$P_{dg,t-1}^{\text{DG}} - P_{dg,t}^{\text{DG}} \leq \text{RD}_{dg} \qquad \forall\ dg, t, \tag{9}$$

$$P_{dg,t}^{\text{DG}} - P_{dg,t-1}^{\text{DG}} \leq \text{RU}_{dg} \qquad \forall\ dg, t, \tag{10}$$

$$P_{d,t}^{\text{DR}} = P_d^{\text{DR-init}} \qquad \forall\ d\in S_{\text{DR}}, \quad t=0, \tag{11}$$

$$P_{d,t}^{\text{DR-min}} \leq P_{d,t}^{\text{DR}} \leq P_{d,t}^{\text{DR-max}} \qquad \forall\ d\in S_{\text{DR}}, t, \tag{12}$$

$$P_{d,t-1}^{\text{DR}} - P_{d,t}^{\text{DR}} \leq \text{LDR}_d \qquad \forall\ d\in S_{\text{DR}}, t, \tag{13}$$

$$P_{d,t}^{\text{DR}} - P_{d,t-1}^{\text{DR}} \leq \text{LPR}_d \qquad \forall\ d\in S_{\text{DR}}, t, \tag{14}$$

$$\sum_{t\in T}\sum_{d\in S_{\text{DR}}} P_{d,t}^{\text{DR}} \leq E_d^{\max} \qquad \forall\ d\in S_{\text{DR}}, \tag{15}$$

$$\text{SOC}_{str,t}^{\text{STR}} = \text{SOC}_{str}^{\text{STR-init}} \qquad \forall\ str, t=0, \tag{16}$$

$$P_{str,t}^{ch} \leq P_{str}^{ch-\max} \qquad \forall\ str, t, \tag{17}$$

$$P_{str,t}^{dch} \leq P_{str}^{\text{STR-}dch-\max} \qquad \forall\ str, t, \tag{18}$$

$$\text{SOC}_{str,t}^{\text{STR}} \leq E_{str}^{\text{STR-max}} \qquad \forall\ str, t, \tag{19}$$

$$\text{SOC}_{str,t}^{\text{STR}} \geq \text{DOD}_{str}, \qquad \forall\ str, t, \tag{20}$$

$$\text{SOC}_{str,t}^{\text{STR}} = \eta_{str}^{ch}\times P_{str,t}^{ch} - \frac{1}{\eta_{str}^{dch}}\times P_{str,t}^{dch} + \text{SOC}_{str,t-1}^{\text{STR}} \quad \forall\ str, t, \tag{21}$$

$$0 \leq \alpha_t^{\text{TEM-sell}} \leq \lambda^{\text{DAM}} \qquad \forall t, \tag{22}$$

$$\alpha_t^{\text{TEM-buy}} \geq \lambda^{\text{DAM}} \qquad \forall\ t, \tag{23}$$

$$P_t^{\text{TEM-buy}}, P_t^{\text{TEM-sell}} \in \arg\Bigg\{\text{Minimize} \left(\alpha_t^{\text{TEM-sell}}P_t^{\text{TEM-sell}} - \alpha_t^{\text{TEM-buy}}P_t^{\text{TEM-buy}}\right) + \sum_{j\in O}\left(\alpha_{j,t}^{\text{TEM-sell-}r}P_{j,t}^{\text{TEM-sell-}r} - \alpha_{j,t}^{\text{TEM-buy-}r}P_{j,t}^{\text{TEM-buy-}r}\right), \tag{24}$$

$$P_t^{\text{TEM-buy}} - P_t^{\text{TEM-sell}} + \sum_j P_{j,t}^{\text{TEM-buy-}r} - P_{j,t}^{\text{TEM-sell-}r} = 0 \qquad : \lambda_t^{\text{TEM}} \tag{25}$$

$$0 \leq P_t^{\text{TEM-buy}} \leq P_t^{\text{TEM-buy-max}} \quad : \mu_t^{\text{buy-min}}, \mu_t^{\text{buy-max}}, \tag{26}$$

$$0 \leq P_t^{\text{TEM-sell}} \leq P_t^{\text{TEM-sell-max}} \quad : \mu_t^{\text{sell-min}}, \mu_t^{\text{sell-max}}, \tag{27}$$

$$0 \leq P_{j,t}^{\mathrm{TEM-buy-}r} \leq P_{j,t}^{\mathrm{TEM-buy-}r\,\max} \quad : \mu_{j,t}^{\mathrm{buy-}r\,\min}, \mu_{j,t}^{\mathrm{buy-}r\,\max} \qquad \forall\, j, \tag{28}$$

$$\left.\begin{array}{l} 0 \leq P_{j,t}^{\mathrm{TEM-sell-}r} \leq P_{j,t}^{\mathrm{TEM-sell-}r\,\max} \\ : \mu_{p,\omega,j,t}^{\mathrm{sell-}r\,\min}, \mu_{p,\omega,j,t}^{\mathrm{sell-}r\,\max} \qquad \forall\, j \end{array}\right\} \qquad \forall\, t. \tag{29}$$

Eq. (2) is the OF problem, which is the MG profit maximization. The first term of the profit is involved with bidding in the TEM. It includes the income of selling energy minus the payment of buying energy. The second term is associated with the real-time operation, which includes the income from the non-flexible load, the DR utility function, operation cost of the DGs, operation cost of ESSs, and the RTM balance cost. It should be noted that the net load interval (i.e., $[D_{d,t}^{\mathrm{LB}}, D_{d,t}^{\mathrm{UB}}]$) and the RTM prices interval (i.e., $[\lambda_t^{\mathrm{RTM-LB}}, \lambda_t^{\mathrm{RTM-UB}}]$) are the prediction intervals, which appear in the OF. With respect to the net load interval, the supply-demand constraint of MG is enforced by Eq. (3). The constraints of DERs, including the controllable DGs, DR, and ESS, are enforced by Eqs. (4)-(10), (11)-(15), and (16)-(21), respectively. Regarding the offered price for selling/buying energy in the TEM, the unfavorable range of the TEM prices is enforced by the right/left-hand side of Eqs. (22) and (23) in comparison with the DAM prices. By Eqs. (24)-(29), the MG enforces the behavior of the rivals in the TEM. The OF is minimizing the reduction in the social welfare (i.e., maximizing the social welfare). The optimization problem of (2)-(29) is bi-level with interval parameters, in which the upper level is the maximization of the MG and the lower level is clearing of the TEM. The variables after the colon show the dual variables of the constraints.

4.2. Single-level interval optimization

In order to solve the proposed mathematical model in Section 4.1, the problem should be cast as a single-level interval optimization. To this purpose, the lower-level problem can be replaced by its KKT conditions. Therefore, a Mathematical Problem with Equilibrium Constraints (MPEC) is formulated by replacing Eqs. (24)-(29) with (30)-(42):

$$\alpha_t^{\mathrm{TEM-sell}} - \lambda_t^{\mathrm{TEM}} + \mu_t^{\mathrm{sell-max}} - \mu_t^{\mathrm{sell-min}} = 0 \qquad \forall\, t, \tag{30}$$

$$-\alpha_t^{\mathrm{TEM-buy}} + \lambda_t^{\mathrm{TEM}} + \mu_t^{\mathrm{buy-max}} - \mu_t^{\mathrm{buy-min}} = 0 \qquad \forall\, t, \tag{31}$$

$$\alpha_{j,t}^{\mathrm{TEM-sell-}r} - \lambda_t^{\mathrm{TEM}} + \mu_{j,t}^{\mathrm{sell-}r\,\max} - \mu_{j,t}^{\mathrm{sell-}r\,\min} = 0 \qquad \forall\, j,t, \tag{32}$$

$$-\alpha_{j,t}^{\mathrm{TEM-buy-}r} + \lambda_t^{\mathrm{TEM}} + \mu_{j,t}^{\mathrm{buy-}r\,\max} - \mu_{j,t}^{\mathrm{buy-}r\,\min} = 0 \qquad \forall\, j,t, \tag{33}$$

$$P_t^{\mathrm{TEM-buy}} - P_t^{\mathrm{TEM-sell}} + \sum_j P_{j,t}^{\mathrm{TEM-buy-}r} - P_{j,t}^{\mathrm{TEM-sell-}r} = 0 \qquad \forall\, t, \tag{34}$$

$$0 \leq P_t^{\mathrm{TEM-buy}} \perp \mu_t^{\mathrm{buy-min}} \geq 0 \qquad \forall\, t, \tag{35}$$

$$0 \leq P_t^{\mathrm{TEM-sell}} \perp \mu_t^{\mathrm{sell-min}} \geq 0 \qquad \forall\, t, \tag{36}$$

$$0 \leq P_{j,t}^{\mathrm{TEM-buy-}r} \perp \mu_{j,t}^{\mathrm{buy-}r\,\min} \geq 0 \qquad \forall\, j,t \tag{37}$$

$$0 \leq P_{j,t}^{\mathrm{TEM-sell-}r} \perp \mu_{j,t}^{\mathrm{sell-}r\,\min} \geq 0 \qquad \forall\, j,t, \tag{38}$$

$$0 \leq \left(P_t^{\mathrm{TEM-buy-max}} - P_t^{\mathrm{TEM-buy}}\right) \perp \mu_t^{\mathrm{buy-max}} \geq 0 \qquad \forall\, t, \tag{39}$$

$$0 \leq \left(P_t^{\mathrm{TEM-sell-max}} - P_t^{\mathrm{TEM-sell}}\right) \perp \mu_t^{\mathrm{sell-max}} \geq 0 \qquad \forall\, t, \tag{40}$$

$$0 \leq \left(P_{j,t}^{\mathrm{TEM-buy-}r\,\max} - P_{j,t}^{\mathrm{TEM-buy-}r}\right) \perp \mu_{j,t}^{\mathrm{buy-}r\,\max} \geq 0 \qquad \forall\, j,t, \tag{41}$$

$$0 \leq \left(P_{j,t}^{\mathrm{TEM-sell-}r\,\max} - P_{j,t}^{\mathrm{TEM-sell-}r}\right) \perp \mu_{j,t}^{\mathrm{sell-}r\,\max} \geq 0 \qquad \forall\, j,t. \tag{42}$$

As mentioned in Section 3.1, we consider the worst case for the interval parameter to guarantee the security of the MG and prevent economic loss. In Eqs. (2) and (3), there are interval parameters. The interval parameter in the OF and interval equality constraint (i.e., Eqs. (2) and (3)) can be handled by the method proposed by Nezamabadi and Vahidinasab [3]. In order the handle the non-linearity associated with the OF (i.e. $\sum_{t\in T} \lambda_t^{\mathrm{TEM-sell}} P_t^{\mathrm{TEM-sell}} - \lambda_t^{\mathrm{TEM-buy}} P_t^{\mathrm{TEM-buy}}$), the strong duality theorem is employed [12]. In the following, linearization of the OF is presented:

$$\sum_{t\in T}\lambda_t^{\text{TEM-sell}}P_t^{\text{TEM-sell}}-\lambda_t^{\text{TEM-buy}}P_t^{\text{TEM-buy}}$$
$$=-\sum_{j\in O}\left(\alpha_{j,t}^{\text{TEM-sell-}r}\times P_{j,t}^{\text{TEM-sell-}r}-\alpha_{j,t}^{\text{TEM-buy-}r}\times P_{j,t}^{\text{TEM-buy-}r}\right)$$
$$-\sum_j \mu_{j,t}^{\text{buy-}r\max}\times P_{j,t}^{\text{TEM-buy-}r\max}$$
$$-\sum_j \mu_{j,t}^{\text{sell-}r\max}\times P_{j,t}^{\text{TEM-sell-}r\max}. \tag{43}$$

The complementarity condition $0 \leq a \perp b \geq 0$ can be replaced by the equivalent linear equations with $a, b \geq 0$, $\varphi \in \{0,1\}$, $a \leq \varphi M_a$, and $b \leq (1-\varphi)M_b$. It should be noted that M_a and M_b are tuned as large numbers to achieve the proper solution [12].

5. Numerical analysis

5.1. Data

In this section, an MG with 4 controllable producers, 4 stochastic producers, one ESS, and one DR is considered for the numerical analysis of the proposed model. In Table 1, the technical and economical characteristics of the producers are given.

The maximum capacity of ESS is equal to 2 MWh and it can charge/discharge 1 MW per hour with 95% efficiency. In addition, the Depth Of Discharge (DOD) and initial State Of Charge (SOC) of the ESS are both 0.1 MW. The minimum required energy by DR is equal to 3 MWh for the total time horizon. The DR can pick up and drop its consumption with the rate of 1 MW/h. Moreover, its minimum and maximum consumption capacities are equal to 0.5 MW and 2.4 MW, respectively. The proposed model is investigated in 4 cases. In each case, the MG is considered seller or buyer in the DAM. Regarding the MG load, the peak and off-peak durations are studied in each case. In Table 2, assumptions for the cases are summarized. It should be noted that the positive and negative values indicate the commitment of the MG to selling and buying in the DAM, respectively.

In Figure 5, the MG net load interval is shown for each case.

In order to investigate the proposed model in the TEM, it is assumed that the MG participates in a TEM with 10 rivals, including 5 sellers and 5 buyers. Offers and bids of the rivals are given in Table 3. As observed, they can provide the maximum of 2 MWh in each hour as a seller or buyer.

5.2. Bidding strategy in the TEM

In the following, the numerical results extracted by the proposed model are given for the considered 4 cases. In Figure 6, the bidding strategy of the MG in TEM

Table 1. Technical and economic characteristics of DGs and RESs.

Unit	Type	Cost coefficient ($/MWh)	Min-max capacity (MW)	Ramp up/down rate (MW/h)
G1	Controllable	27.7	1-5	2.5
G2	Controllable	39.1	1-5	2.5
G3	Controllable	61.3	0.2-3	0.5
G4	Controllable	125.0	0.2-3	—
G5	Stochastic	—	0-0.5	—
G6	Stochastic	—	0-0.5	—
G7	Stochastic	—	0-0.5	—
G8	Stochastic	—	0-0.5	—

Table 2. Assumptions of cases.

	DAM commitment (MWh, $/MWh)				MG load
	Time 1	Time 2	Time 3	Time 4	
Case 1	(1, 86.67)	(2.3, 123.83)	(2.4, 120.66)	(2.2, 102.38)	Peak
Case 2	(1, 86.67)	(2.3, 123.83)	(2.4, 120.66)	(2.2, 102.38)	Off-peak
Case 3	(–10.5, 15)	(–12.3, 15.5)	(–12.8, 16.8)	(–11.2, 15.2)	Peak
Case 4	(–10.5, 15)	(–12.3, 15.5)	(–12.8, 16.8)	(–11.2, 15.2)	Off-peak

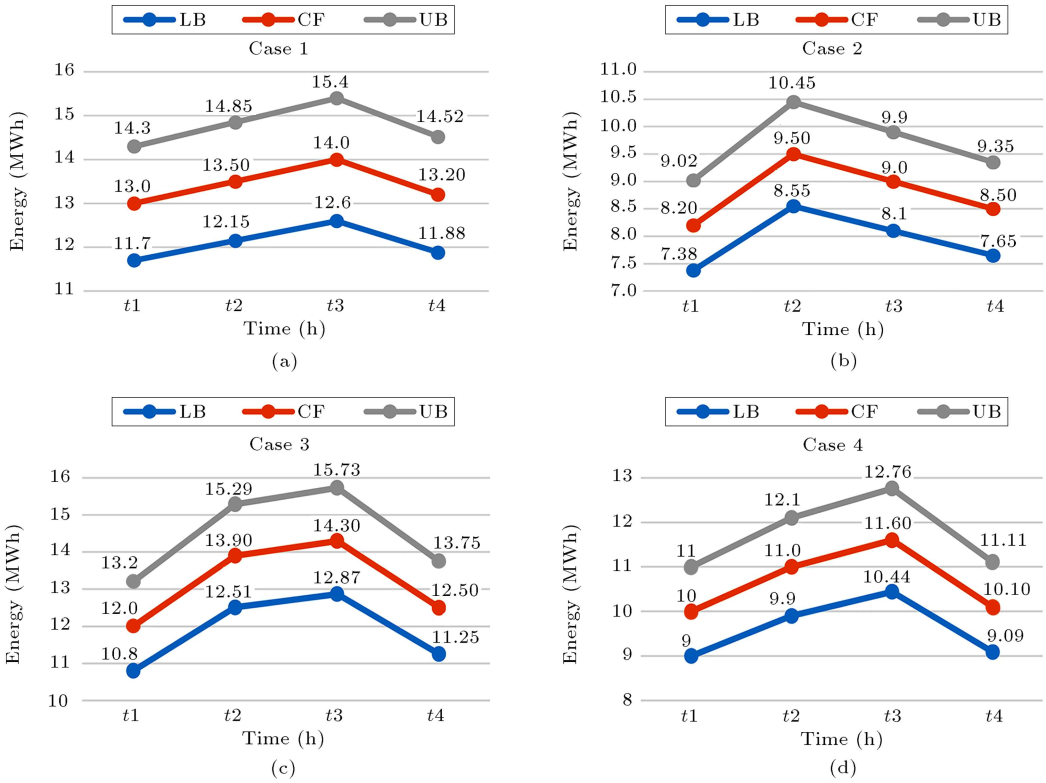

Figure 5. The MG net load interval: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

Table 3. Offers and bids of the rivals in the TEM.

			Time 1	**Time 2**	**Time 3**	**Time 4**
Case 1 & Case 2	Buyers' bid	B1	(1, 107.0)	(1, 152.90)	(1, 149.0)	(1, 126.4)
		B2	**(0.25, 90.1)**	**(0.25, 128.8)**	**(0.25, 125.5)**	**(0.25, 106.5)**
		B3	**(0.25, 89.0)**	**(0.25, 127.2)**	**(0.25, 123.9)**	**(0.25, 105.1)**
		B4	**(0.25, 88.4)**	**(0.25, 126.3)**	**(0.25, 123.1)**	**(0.25, 104.4)**
		B5	**(0.25, 87.5)**	**(0.25, 125.1)**	**(0.25, 121.9)**	**(0.25, 103.4)**
	Sellers' offer	S1	(1, 66.7)	(1, 95.3)	(1, 92.9)	(1, 78.8)
		S2	(0.25, 72.8)	(0.25, 104.0)	(0.25, 101.3)	(0.25, 85.9)
		S3	(0.25, 78.8)	(0.25, 112.6)	(0.25, 109.8)	**(0.25, 93.1)**
		S4	**(0.25, 79.7)**	**(0.25, 113.9)**	(0.25, 111.0)	**(0.25, 94.1)**
		S5	**(0.25, 84.9)**	**(0.25, 121.3)**	**(0.25, 118.2)**	**(0.25, 100.3)**
Case 3 & Case 4	Buyers' bid	B1	**(1, 17.8)**	**(1, 18.2)**	**(1, 18.5)**	**(1, 18.0)**
		B2	**(0.25, 17.6)**	**(0.25, 18.0)**	**(0.25, 18.3**	**(0.25, 17.9)**
		B3	**(0.25, 17.4)**	**(0.25, 17.6)**	**(0.25, 17.9)**	**(0.25, 17.5)**
		B4	**(0.25, 16.9)**	**(0.25, 17.3)**	**(0.25, 17.8)**	**(0.25, 17.0)**
		B5	**(0.25, 16.8)**	**(0.25, 17.0)**	**(0.25, 17.5)**	**(0.25, 16.9)**
	Sellers' offer	S1	(1, 10.8)	(1, 11.0)	(1, 11.8)	(1, 10.9)
		S2	(0.25, 11.0)	(0.25, 11.4)	(0.25, 12.3)	(0.25, 11.2)
		S3	(0.25, 11.3)	(0.25, 11.9)	(0.25, 12.6)	(0.25, 11.7)
		S4	(0.25, 11.8)	(0.25, 12.1)	(0.25, 13.3)	(0.25, 11.8)
		S5	(0.25, 12.0)	(0.25, 12.8)	(0.25, 14.0)	(0.25, 12.3)

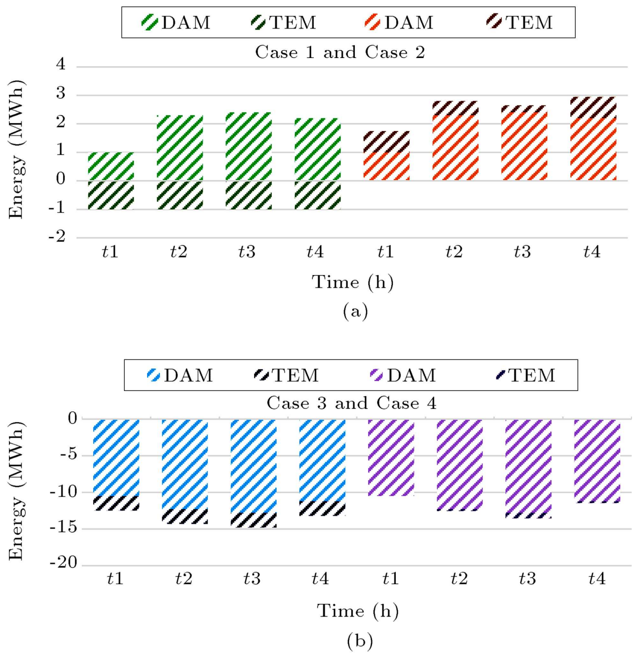

Figure 6. The DAM commitments and bidding values in TEM: (a) Cases 1 and 2 and (b) Cases 3 and 4.

and the commitments of the DAM are shown. The positive and negative values indicate the roles of the buyer and the seller, respectively. In Cases 1 and 2, the MG sells energy to the DAM one day before. Therefore, the price of the DAM is so high that it is profitable for the MG to employ its DERs for producing energy. After the DAM clearing, the MG deals with net load uncertainty in peak and off-peak durations in Cases 1 and 2, respectively. In Figure 6(a), it is shown that the MG should buy the energy deficit as much as 1 MWh in the TEM during the peak (i.e., Case 1). Moreover, it is shown that the MG can sell its excess energy in the TEM during the off-peak (i.e., Case 2).

In Cases 3 and 4, the MG buys energy from the DAM one day before. Therefore, the price of the DAM is not so high to be profitable for the MG to employ its DERs for producing energy. However, after the DAM clearing, the MG faces net load uncertainty in peak and off-peak durations in Cases 3 and 4, respectively. By the realization of the peak load or off-peak, the MG can provide its energy deficit by the TEM; see Figure 6(b).

In Table 4, the pairs of quantity and price $(P^{\text{TEM}-\text{buy}}, \alpha^{\text{buy}})$, which are submitted to the TEM, are given. Regarding the MCP of the TEM, in Table 3, the bold font shows the rejected offers and the normal font shows the accepted bids and offers. In Cases 1, 3, and 4, the MG tends to buy energy more expensive than the DAM price in the TEM instead of buying energy in RTM prices, which are the highest. In Case 3, the MG tends to sell energy cheaper than the DAM price in the TEM instead of selling energy in RTM prices, which are the lowest.

5.3. The optimal operation of DERs in the TEM

In Figure 7, the average output of the DERs is shown. The total production of the DGs is given in Figure 7(a). During times 1 and 2, the DGs produce their maximum capability (i.e., more than 15 MW in average) in Case 1 and the TEM prices (i.e., 128.8 and 125.5 \$/MWh; see Table 3) are greater than the prices of all controllable DGs. In Case 2, the TEM prices are still high, but lower than the operation cost of DG4 (i.e., 125.0 \$/MWh). Therefore, the total production of the DGs (i.e., total production of DG1+DG2+DG3) decreases to 13 MWh. Finally, in Cases 3 and 4, the TEM prices are too much lower than the production cost of the DGs. Therefore, they produce no energy in TEM.

The SOC of the ESS is illustrated in Figure 7(b). In all cases, the ESS is charged during time 1 with the lowest price in the TEM (see Table 3) and it releases its energy to the MG during times 2 and 3 with the highest prices of TEM.

Table 4. The MG offer and bid in the TEM, and market clearing price of the TEM.

	MG role in TEM		Time 1	Time 2	Time 3	Time 4
Case 1	Buyer	$(P^{\text{TEM}-\text{buy}}, \alpha^{\text{buy}})$	(−1, 90.1)	(−1, 128.8)	(−1, 125.5)	(−1, 106.5)
		λ^{TEM}	90.1	128.8	125.5	106.5
Case 2	Seller	$(P^{\text{TEM}-\text{buy}}, \alpha^{\text{buy}})$	(0.75, 78.8)	(0.5, 113.9)	(0.25, 84.462)	0.75, 93.1)
		λ^{TEM}	78.8	113.9	118.2	93.1
Case 3	Buyer	$(P^{\text{TEM}-\text{buy}}, \alpha^{\text{buy}})$	(−2, 17.8)	(−2, 18.2)	(−2, 18.5)	(−2, 18)
		λ^{TEM}	17.8	18.2	18.5	18
Case 4	Buyer	$(P^{\text{TEM}-\text{buy}}, \alpha^{\text{buy}})$	(0, 16.8)	(−0.25, 17)	(−0.75, 17.9)	(−0.25, 16.9)
		λ^{TEM}	16.8	17	17.9	16.9

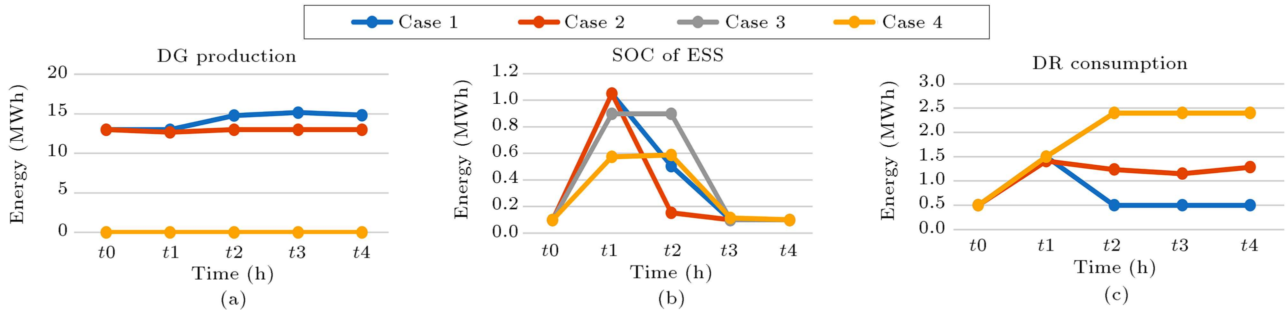

Figure 7. DERs outputs: (a) DG production, (b) SOC of ESS, and (c) DR consumption.

In Figure 7(c), the DR consumption is illustrated. In Case 1, the MG is a buyer in the TEM and the price of TEM is greater than the DR consumption cost (i.e., 95 $/MWh). Therefore, the DR consumes its minimum energy during the entire time horizon. In Case 2, the TEM prices in times 1, 3, and 4 are lower than 95$/MWh. Thus, the DR consumes more than its minimum capability (i.e., 3 MWh). In Cases 4 and 5, in all times, the TEM prices are lower than the DR cost. Thus, the maximum capability of the energy consumption is employed.

5.4. Profitability of the TEM for the MG

In this section, the profit of the MG is considered with and without participation in the TEM. In Table 5, the profit of the MG is investigated in detail. By the participation in the DAM, the MG earns $886.3 in Cases 1 and 2, and pays $-733.4 in Cases 3 and 4. In Cases 1, 3, and 4, the TEM profit is negative, because of buying energy in TEM, and equal to $-450.9, $-145.0, and $-21.9, respectively. In Case 2, net loads and its uncertainty are at lowest (see Figure 5(b)); the TEM prices are high enough to make the production of DERs profitable; and the MG can earn $215.4 from TEM.

By comparing total profits of the cases with and without considering TEM, the profits of MG increase by 3.1%, 0.9%, 2.7%, and 0.2% in 4 cases only for 4 hours. On average, the MG can increase its profit by 10.2% (i.e., 6×1.7%) by participating in the TEM 6 times a day (i.e., every 4 hours).

6. Conclusion

In this paper, a bidding strategy for the MG in the transactive energy market was proposed based on a bi-level optimization with interval coefficient, in which the profit of the MG was maximized at the upper level and the clearing of the TEM market was considered as the lower-level problem. In order to solve the proposed model, the problem was recast as single-level interval optimization by using KKT conditions and interval optimization concept. In addition, the uncertainty of the net loads was handled by interval optimization. The proposed framework proves that:

- The MG tends to buy energy more expensive than the DAM price in the TEM instead of buying energy in RTM prices, which are the highest;
- The MG tends to sell energy cheaper than the DAM price in the TEM instead of selling energy in RTM prices, which are the lowest;
- Regarding the profitability of the TEM for the MG,

Table 5. The MG profits.

		DAM profit ($)	TEM profit ($)	RTM profit ($)	Total profit ($)
Case 1	With TEM	886.3	–450.9	–346.2	2141.7
	Without TEM		—	–624.4	2075.7
Case 2	With TEM	886.3	215.4	86.2	2611.3
	Without TEM		—	117.5	2586.6
Case 3	With TEM	–733.4	–145.0	–134.7	656.5
	Without TEM		—	–297.2	639.1
Case 4	With TEM	–733.4	–21.9	–70.2	684.2
	Without TEM		—	–93.4	682.8

it can earn 1.7% more profit in every 4 hours by participation in the TEM. Consequently, in 24 hours of participation in TEM, it can increase its profit to 10.2%.

The future research can be focused on the extent of participation of the MGs in TEM with distribution grid cost allocation in the proposed model.

References

1. Rahimi, F., Ipakchi, A., and Fletcher, F. "The changing electrical landscape: end-to-end power system operation under the transactive energy paradigm", *IEEE Power and Energy Magazine*, **14**(3), pp. 52-62 (2016).
2. Kristov, L., Martini, P.D., and Taft, J.D. "A Tale of two visions: Designing a decentralized transactive electric system", *IEEE Power and Energy Magazine*, **14**(3), pp. 63-69 (2016).
3. Nezamabadi, H. and Vahidinasab, V. "Market bidding strategy of the microgrids considering demand response and energy storage potential flexibilities", *IET Generation, Transmission & Distribution*, **13**(8), pp. 1346-1357 (2019).
4. Morstyn, T., Farrell, N., Darby, S.J., et al. "Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants", *Nature Energy*, **3**(2), pp. 94-101 (2018).
5. Morales, J.M., Conejo, A.J., Madsen, H., et al. "Integrating renewables in electricity markets: operational problems", Springer Science & Business Media, New York, USA (2013).
6. Nikolaidis, A.I., Charalambous, C.A., and Mancarella, P. "A graph-based loss allocation framework for transactive energy markets in unbalanced radial distribution networks", In *IEEE Transactions on Power Systems*, **34**(5), pp. 4109-4118 (2019).
7. DiSilvestre, M.L., Gallo, P., Ippolito, M.G., et al. "A technical approach to the energy blockchain in microgrids", *IEEE Transactions on Industrial Informatics*, **14**(11), pp. 4792-4803 (2018).
8. Moret, F., Baroche, T., Sorin, E., et al. "Negotiation algorithms for peer-to-peer electricity markets: Computational properties", In *2018 Power Systems Computation Conference (PSCC)*, Dublin, Ireland, pp. 1-7 (2018).
9. Morstyn, T., Teytelboym, A., and McCulloch, M.D. "Bilateral contract networks for peer-to-peer energy trading", *IEEE Transactions on Smart Grid*, **10**(2), pp. 2026-2035 (2018).
10. Morabito, V., *Business Innovation Through Blockchain*, Springer International Publishing, Cham, Switzerland (2017).
11. Liu, G., Xu, Y., and Tomsovic, K. "Bidding strategy for microgrid in day-ahead market based on hybrid stochastic/robust optimization", *IEEE Transactions on Smart Grid*, **7**(1), pp. 227-237 (2016).
12. Kazempour, S.J. and Zareipour, H. "Equilibria in an oligopolistic market with wind power production", *IEEE Transactions on Power Systems*, **29**(2), pp. 686-697 (2014).

Biographies

Hossein Nezamabadi received his BSc and MSc in Electrical Engineering from Shahid Beheshti University in 2011 and 2014, respectively. He is currently pursuing his PhD in Electrical Engineering at Shahid Beheshti University. His areas of interest include integration of renewable energy sources into electricity markets, microgrids, and virtual power plants.

Vahid Vahidinasab received the BSc degree from K.N. Toosi University of Technology, Tehran, Iran, in 2004, and the MSc and PhD degrees from Iran University of Science and Technology, Tehran, Iran, in 2006 and 2010, respectively, all in Electrical Engineering. Since 2010, he has been with the Department of Electrical Engineering, Shahid Beheshti University (SBU). He has also founded and managed SOHA Smart Energy Systems Laboratory at SBU. Dr. Vahidinasab has demonstrated a consistent track record of attracting external fund, managed several national and international projects, and collaborated with several large and complex national/international projects. He was considered as one of the outstanding reviewers of the IEEE Transactions on Sustainable Energy and top 1% reviewers in engineering according to Publons Peer Review Awards in 2018. His research interest is oriented towards different research and technology aspects of energy systems integration, smart grids/microgrids/nanogrids design, operation and economics, and application of machine learning and optimization methods to energy system studies (modelling, forecasting, and optimization). Dr. Vahidinasab is a senior member of the IEEE and a member of the IEEE Power and Energy Society (PES) as well as IEEE Smart Grid Society. He is also an associate editor of the IET Generation, Transmission & Distribution, and IET Smart Grid.