Microgrids Bidding Strategy in a Transactive Energy Market

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Abstract: This paper proposes microgrid (MG) bidding strategy in the transactive energy market (TEM), in which market participants are able to negotiate and trade by a new-designed smart contract (SC) in a peer-to-peer way. In such a market, MG can balance its deviations, which are the resultant of the intermittency of the renewable energy sources, and the volatility of the load. In this paper, the uncertainty is handled by interval optimization. By participation in the TEM, the MG bidding problem is a bi-level optimization with interval coefficient, in which the MG’s profit maximizes in the upper level and the rivals’ behaviour in the TEM are modelled in the lower level. In order to solve aforementioned problem, the proposed model recasts as a single-level interval optimization problem by the Karush-Kuhn-Tucker (KKT) conditions and the interval optimization concept. Simulation results show the applicability of the proposed model and realize the 1.7% increase in the MG profit for a 4-hour duration basis TEM.

Keywords: Bidding strategy, smart contract, energy blockchain, transactive energy market, microgrids, bi-level optimization, uncertainty, interval coefficient modelling.

1. Introduction

Due to the widespread use of intermittent renewable energy sources (RESs), the emergence of new technologies, and extension of the communication and control to the end-user, the power system landscape is undergoing significant changes [1]. By using the new technology, which is affected the economic and control techniques, the transactive energy system (TES) can balance the supply and demand via a value-based system [2]. Regarding the operation of the power system, the passive distribution system moves toward an active one, in which microgrids (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, are undergoing widespread changes. By considering the traditional business model, the MGs can participate in the day-ahead market (DAM). Then, due to the uncertainties in the forecast of RESs production and loads consumption, they are forced to deal with its imbalances by the real-time market (RTM) [3]. However, by the emerging transactive MG controller, the MG can overcome the uncertainties by the transactive energy market (TEM) instead of participating in the RTM, whose prices are unfavourable than 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) under the decentralized pricing mechanisms [6]. Some technical issues of energy transaction (e.g. loss allocation) inside of the MGs are
considered in the [7]. The loss allocation methods, which are appropriate for the peer-to-peer trades, are proposed in the [6]. The application of blockchain technology in the MGs without the requirement of central intermediaries is proposed in [7]. In this paper, the energy blockchain includes power losses, which the losses attribution to each energy transaction (i.e. each block) in the MG is assigned by the independent system operator (ISO).

On the other hand, the second sets of works focus on the consensus algorithm and market design for the market participants [8]. In the self-managed decentralized TEM, any need for an intermediary between two parties is removed by the blockchain technology, which is originally used for the tracking economic transactions without the need of 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 into TEM is one of the main challenges faced by the MG manager. In consideration of the foregoing, the objective of this paper is to propose the bidding strategy of an MG as a transactive agent, and is 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 threefold as following:

1) In comparison with the previous works, 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 maximizes in the upper level, and the clearing of the TEM market is considered as the lower level problem. In order to solve the proposed model, the problem recasts 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 our rivals (e.g aggregators or etc.).

3) Simulation results on an illustrative MG with four controllable DGs, four stochastic producers, one 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, whose prices are the most expensive price. Also, the MG tends to sell energy cheaper than the DAM price in the TEM, instead of selling energy in RTM prices, whose prices are the cheapest price. By investigating the profitability of the TEM for the MG, it can earn 1.7% more profit from every 4-hour by the participation in the TEM. Consequently, by 24-hour participation in TEM, it can increase its profit to 10.2%.

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

2. Transactive Microgrids

2.1. The Elements of Transactive MG

In Fig. 1, the necessary layers for the formation of a transactive MG are shown. The first layer of a transactive MG is the physical layer. In the physical layer, there are sets of the DERs, including RESs, distributed generations (DGs), energy storage systems (ESSs) and demand responses (DRs). As the first necessity of the TES, the MG should be visible, controllable and flexible. In order to obtain visibility, controllability and flexibility, the components of MG should be equipped to the sensors and controller in the technical layer. The technical layer includes all of the electrical and mechanical equipment, which make the MG system visible and controllable. The network layer is an interface between the technical layer and the business layer. Hence, the network layer should receive the command of the MG manager and send the command to the technical layer. Also, should receive the real-time operation characteristics (i.e. production, consumption rate, etc.) and send 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, the scheduling of the DERs is determined by the algorithms and procedures, which are made by the MG manager. Finally, in the market layer, the market place rules are determined by the structure of markets (i.e. payment rules, time scheduling rules, etc.). By the following, the evolution of transactions and the market structure are given.

2.2. The Evolution of the transactions

Traditional transaction models rely on a central authority to act in 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 schedules all of the market participants in a centralized manner, which is called the pool market.

Under the TE paradigm, the new transaction models are achieved by enabling peer-to-peer and smart contracts (SCs) between transactive agents in 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 is 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 permit to read and write data in the public blockchain, only
permitted participants can read and write data in the private one. By the private blockchain, ISO can guarantee the secure and efficient operation of the grid. Based on the rules of the consensus model, each participant (i.e. MGs, prosumers, storages and etc.) broadcast changes by forming new blocks and requesting validation. Once validated by the distribution system TE platform, the block is added to everyone’s chain. In Fig. 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 granted to sign the SC instead of their customers.

2.3. Transactive energy market Design

Regarding the uncertainties of the RES productions and the load consumptions, the uncertainty level is decreased from one day before with fully-uncertain level to near the real-time with a certain level. Currently, the producers/consumers should offer/bid their fully-uncertain production/consumptions to the DAM. Next, the commitments of the producers/consumers are determined after the clearing of the DAM. Then, 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 avoid 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. The Equation (1) shows the relation of the MCP of the DAM, TEM and RTM. The MCPs of the DAM and RTM make the price floor and cap for the buyer (i.e. $\lambda^{\text{TEM}} \in [\lambda^{\text{DAM}}, \lambda^{\text{RTM}}]$), and make the price cap and floor for the seller (i.e. $\lambda^{\text{TEM}} \in [\lambda^{\text{RTM}}, \lambda^{\text{DAM}}]$), respectively. Thus, by moving from DAM to RTM, the favourability of the MCP is decreased for the stochastic sellers and buyers.

\[
\begin{align*}
\lambda^{\text{DAM}} & \leq \lambda^{\text{TEM}} \leq \lambda^{\text{RTM}} & \text{for buyer} \\
\lambda^{\text{RTM}} & \leq \lambda^{\text{TEM}} \leq \lambda^{\text{DAM}} & \text{for seller}
\end{align*}
\]

(1)

In the Fig. 3, the production level 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 A and B value, which are fully-uncertain, to the DAM (see Fig. 3(a)). It is assumed that A and B value are accepted in the DAM. Therefore, the producer 1 and 2 are paid by the MCP of DAM (i.e. $\lambda^{\text{DAM}}$) after the clearing process.

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

Finally, the real-time stage is illustrated in Fig. 3(d). In the real-time, the 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 the C. Thus, producer 2 has to sell its excess production (i.e. C-D) by least favourable price in the RTM. In this paper, the TEM implements every 4-hour in a day. It would be able to implement 6 times in a day.

2.4. Designing Smart Contract in the Transactive Energy Market

The SC of energy transaction should cover the scenario for buying and selling energy, which requires ISO validation. Sellers can list their flexibility 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 seller validate the trade, they will confirm the transaction again before the contract is agreed.

There are three participants in the SC. There are various actions, which player can take. The logic written in the SC will modify the state accordingly based on which actions are taken. The application roles in the SC are as 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 who validates the energy transaction from the security point of view and allocates the side fees of the energy transaction between seller and buyer.

In the Fig.4, the state transition diagram articulates the possible flows and the various transition functions at each state. Each user is only allowed to take certain actions depending on the application role. A happy path (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. Microgrid Business Model Under Transactive Energy Paradigm

In the previous business model of the MG, it can participate in the DAM, and then it can balance its deviations from the RTM [3, 11]. As a business plan, the MG can decide to sign a SC with load aggregators, other MG for energy procurement by using blockchain technology. Therefore, between DAM and RTM, the MG can procure its 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, the interval prediction is employed in this paper. In the prediction of intervals, it is common to forecast the central prediction intervals of the uncertain parameter with a nominal coverage rate of $\gamma\%$ [5]. The main advantage of the prediction interval is that it can provide forecast users with a feeling about the level of forecast uncertainty for the coming period. In comparison with scenario forecast, there is no need to 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 level (UB) of the prediction interval.

By the application of the interval prediction, the interval optimization is employed to gain the bidding strategy of the MG in the TEM market. In the interval optimization, the main problem is reaching the optimum value of the objective function (OF) with considering the interval parameter, which can be in OF or in constraints. This optimum value may be the worst or the best possible optimal solution. The net load is a parameter, which 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, the high volatility makes the RTM price forecast impossible. Therefore, the MG considers the worst case of the RTM prices to avoid 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 with a two-stage decision-making problem. In the first stage, the MG bids in the TEM, whose structure are given in section 2.3. To best bidding strategy in the TEM, the MG should compete with its rivals in this stage. She or he should model the behavior of its rival. Therefore, the clearing of the TEM is the main problem of the MG in this stage. Then, after clearing the TEM, it should balance its real-time deviation by the RTM prices in the second-stage.

4. Model formulation

4.1. Bi-level optimization with interval coefficient

In the proposed model, the MG should maximize the profit. By the following, the mathematical model of the bidding problem of the MG in TEM is given.
Maximize Profit = \sum_{t \in T} \left( \lambda_{t}^{\text{TEM-sell}} P_{t}^{\text{TEM-sell}} - \lambda_{t}^{\text{TEM-buy}} P_{t}^{\text{TEM-buy}} \right) + \sum_{d \in S_{d, t}} \left( \sum_{s \in S_{d, t}} P_{d, s, t}^{R_{d}} + C_{d, s}^{D_{d, t}} \right) + \sum_{d \in S_{d, t}} \left[ \lambda_{t}^{\text{TEM-sell}} - \lambda_{t}^{\text{TEM-buy}} \right] P_{t}^{R_{d}} \quad (2)

Subject to:

\[ \sum_{s \in S_{d, t}} P_{d, s, t}^{D_{d, t}} \geq \text{MUT}_{d, t}^{D_{d, t}}, \forall d, t \] \quad (3)

\[ \sum_{s \in S_{d, t}} 1 - P_{d, s, t}^{D_{d, t}} \leq \text{MTD}_{d, t}^{D_{d, t}}, \forall d, t \] \quad (4)

\[ P_{d, s, t}^{D_{d, t}} \leq P_{d, t}^{D_{d, t}}, \forall d, s, t \] \quad (5)

\[ J_{d, s, t}^{D_{d, t}} - K_{d, s, t}^{D_{d, t}} = I_{d, s, t}^{D_{d, t}} - P_{d, s, t}^{D_{d, t}}, \forall d, s, t \] \quad (6)

\[ J_{d, s, t}^{D_{d, t}} + K_{d, s, t}^{D_{d, t}} \leq 1 \] \quad (7)

\[ \sum_{s \in S_{d, t}} P_{d, s, t}^{D_{d, t}} \leq \text{MUT}_{d, t}^{D_{d, t}} - 1 \] \quad (8)

\[ \sum_{s \in S_{d, t}} 1 - P_{d, s, t}^{D_{d, t}} \leq \text{MTD}_{d, t}^{D_{d, t}} - 1 \] \quad (9)

\[ P_{d, s, t}^{D_{d, t}} \leq P_{d, s, t}^{D_{d, t}} \leq P_{d, s, t}^{D_{d, t}} \leq P_{d, t}^{D_{d, t}}, \forall d, s, t \] \quad (10)

\[ P_{d, s, t}^{D_{d, t}} \leq 0 \] \quad (11)

\[ P_{d, s, t}^{D_{d, t}} \leq P_{d, s, t}^{D_{d, t}} \leq P_{d, s, t}^{D_{d, t}} \leq P_{d, t}^{D_{d, t}}, \forall d, s, t \] \quad (12)

\[ \sum_{t \in T} d \in S_{d, t} \] \quad (13)

\[ \sum_{s \in S_{d, t}} P_{d, s, t}^{D_{d, t}} \leq E_{s}^{D_{d, t}}, \forall d, s \] \quad (14)

\[ \sum_{s \in S_{d, t}} P_{d, s, t}^{D_{d, t}} \leq E_{s}^{D_{d, t}}, \forall d, s \] \quad (15)

\[ \text{SOC}_{s, t}^{\text{str}} = \text{SOC}_{s, t}^{\text{str-init}} \] \quad (16)

\[ \eta_{s}^{D_{d, t}} \leq \text{SOC}_{s, t}^{\text{str}} \] \quad (17)

\[ 0 \leq \lambda_{t}^{\text{TEM-sell}} \leq \lambda_{t}^{\text{DAM}}, \forall t \] \quad (18)

\[ \lambda_{t}^{\text{TEM-buy}} \geq \lambda_{t}^{\text{DAM}}, \forall t \] \quad (19)

\[ p_{t}^{\text{TEM-sell}}, p_{t}^{\text{TEM-buy}} \in \arg \left\{ \min \left( \lambda_{t}^{\text{TEM-sell}} P_{t}^{\text{TEM-sell}} - \lambda_{t}^{\text{TEM-buy}} P_{t}^{\text{TEM-buy}} \right) + \sum_{j \in J} \left( \lambda_{j}^{\text{TEM-sell-r}} P_{j, t}^{\text{TEM-sell-r}} - \lambda_{j}^{\text{TEM-buy-r}} P_{j, t}^{\text{TEM-buy-r}} \right) \right\} \] \quad (20)
\[ P_{i}^{\text{TEM-buy}} - P_{i}^{\text{TEM-sell}} \sum_{j} P_{j,t}^{\text{TEM-buy-r}} - P_{j,t}^{\text{TEM-sell-r}} = 0 \quad : \alpha_{i}^{\text{TEM}} \]  
\[ 0 \leq P_{i}^{\text{TEM-buy}} \leq P_{i}^{\text{TEM-buy-max}} : \mu_{i}^{\text{buy-min}}, \mu_{i}^{\text{buy-max}} \]  
\[ 0 \leq P_{i}^{\text{TEM-sell}} \leq P_{i}^{\text{TEM-sell-max}} : \mu_{i}^{\text{sell-min}}, \mu_{i}^{\text{sell-max}} \]  
\[ 0 \leq P_{j,t}^{\text{TEM-buy-r}} \leq P_{j,t}^{\text{TEM-buy-r-max}} : \mu_{j,t}^{\text{buy-r-min}}, \mu_{j,t}^{\text{buy-r-max}} \forall j \]  
\[ 0 \leq P_{j,t}^{\text{TEM-sell-r}} \leq P_{j,t}^{\text{TEM-sell-r-max}} : \mu_{p,o,j,t}^{\text{sell-r-min}}, \mu_{p,o,j,t}^{\text{sell-r-max}} \forall j \]  
\[ \forall t \]  
\[ \alpha_{i}^{\text{TEM-sell}} - \alpha_{i}^{\text{TEM-buy}} + \mu_{i}^{\text{sell-max}} - \mu_{i}^{\text{sell-min}} = 0 \quad \forall t \]  
\[ -\alpha_{j,t}^{\text{TEM-sell-r}} + \alpha_{j,t}^{\text{TEM-buy-r}} + \mu_{j,t}^{\text{sell-r-max}} - \mu_{j,t}^{\text{sell-r-min}} = 0 \quad \forall j, t \]  
\[ -\alpha_{j,t}^{\text{TEM-buy-r}} + \alpha_{j,t}^{\text{TEM-sell-r}} + \mu_{j,t}^{\text{buy-r-max}} - \mu_{j,t}^{\text{buy-r-min}} = 0 \quad \forall j, t \]  
\[ \alpha_{j,t}^{\text{TEM-buy-r}} - \alpha_{j,t}^{\text{TEM-sell-r}} + \sum_{j} P_{j,t}^{\text{TEM-buy-r}} - P_{j,t}^{\text{TEM-sell-r}} = 0 \quad \forall t \]  
\[ 0 \leq P_{i}^{\text{TEM-buy}} \perp \mu_{i}^{\text{buy-min}} \geq 0 \quad \forall t \]  
\[ 0 \leq P_{i}^{\text{TEM-sell}} \perp \mu_{i}^{\text{sell-min}} \geq 0 \quad \forall t \]  
\[ 0 \leq P_{j,t}^{\text{TEM-buy-r}} \perp \mu_{j,t}^{\text{buy-r-min}} \geq 0 \quad \forall j, t \]  

Equation (1) is the problem of OF, which is the MG profit maximization. The first term of the profit is involved with the bidding to the TEM. It includes the income of selling energy minus the payment of the 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, the operation cost of ESSs and the RTM balance cost. It should be noted that the net load interval (i.e. \([D_{d,t}^{LB}, D_{d,t}^{UB}]\)) and the RTM prices interval (i.e. \([\lambda_{\text{RTM-LB}}, \lambda_{\text{RTM-UB}}]\)) are the prediction intervals, which is appeared in the OF. With respect to the net load interval, the supply-demand constraint of MG is enforced by the Equations (3). The constraints of DERs, including the controllable DGs, DR, and ESS, are enforced by the Equations (4)-(10), (11)-(16), and (17)-(22), respectively. Regarding the offering price for the selling/buying energy in the TEM, the unfavorable range of the TEM price is enforced by the right/left hand side of the Equations (23) and (24) in comparison with the DAM prices. By the Equations (25)-(30), the MG enforce the rivals’ behavior in the TEM. The problem OF is minimizing the minus of the social welfare (i.e. maximizing the social welfare). The optimization problem of (2)-(30) is a bi-level optimization with interval parameters, in which the upper level is the maximization of the MG, and the lower level is the 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 resulted by replacing the Equations (31)-(43) instead of (25)-(30):

\[ \alpha_{i}^{\text{TEM-sell}} - \alpha_{i}^{\text{TEM-buy}} + \mu_{i}^{\text{sell-max}} - \mu_{i}^{\text{sell-min}} = 0 \quad \forall t \]  
\[ -\alpha_{j,t}^{\text{TEM-sell-r}} + \alpha_{j,t}^{\text{TEM-buy-r}} + \mu_{j,t}^{\text{sell-r-max}} - \mu_{j,t}^{\text{sell-r-min}} = 0 \quad \forall j, t \]  
\[ -\alpha_{j,t}^{\text{TEM-buy-r}} + \alpha_{j,t}^{\text{TEM-sell-r}} + \mu_{j,t}^{\text{buy-r-max}} - \mu_{j,t}^{\text{buy-r-min}} = 0 \quad \forall j, t \]  
\[ \alpha_{j,t}^{\text{TEM-buy-r}} - \alpha_{j,t}^{\text{TEM-sell-r}} + \sum_{j} P_{j,t}^{\text{TEM-buy-r}} - P_{j,t}^{\text{TEM-sell-r}} = 0 \quad \forall t \]  
\[ 0 \leq P_{i}^{\text{TEM-buy}} \perp \mu_{i}^{\text{buy-min}} \geq 0 \quad \forall t \]  
\[ 0 \leq P_{i}^{\text{TEM-sell}} \perp \mu_{i}^{\text{sell-min}} \geq 0 \quad \forall t \]  
\[ 0 \leq P_{j,t}^{\text{TEM-buy-r}} \perp \mu_{j,t}^{\text{buy-r-min}} \geq 0 \quad \forall j, t \]
As it mentioned before in 3.1, we consider the worst case of interval parameter in reason of guaranteeing the security of the MG and avoiding the economic loss. In Equations (2) and (3), there are interval parameters. The interval parameter in the OF and an interval equality constraint (i.e. Equation (2) and (3)) can be handled by the way which is proposed in the [3]. In order the handle the non-linearity associated with the OF (i.e. \( \sum_{t \in \Omega} \alpha_{j,T} P_{j,T}^{\text{sell}} - \lambda_{j,T} P_{j,T}^{\text{buy}} \)), the strong duality theorem is employed [12]. By the following, the linearization of the OF is given:

\[
\sum_{t \in \Omega} \alpha_{j,T} P_{j,T}^{\text{sell}} - \lambda_{j,T} P_{j,T}^{\text{buy}} = -\sum_{t \in \Omega} \left( \alpha_{j,T} P_{j,T}^{\text{sell}} - \lambda_{j,T} P_{j,T}^{\text{buy}} \right)
\]

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

5. Numerical analysis

5.1. Data

In this section, an MG with four controllable producers, four 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 2MWh and it can charge/discharge 1MW per hour with 95% efficiency. In addition, the DOD and initial SOC of the ESS are both 0.1 MW. The minimum required energy of DR is equal to 3MWh for the total time horizon. The DR can pick-up and drop its consumption with the rate of 1MW/h. Moreover, its minimum and maximum consumption capacity are equal to 0.5 MW and 2.4MW, respectively. The proposed model is investigated in 4 cases. In each case, the MG load, the peak and off-peak duration are studied in each case. In Table 2, cases assumptions are summarized. It should be noted that the positive and negative value indicates the commitment of the MG to sell or buy in the DAM, respectively.

In the Fig. 5, the MG net load interval is shown for each cases.

In order to investigate the proposed model in the TEM market, it is assumed that the MG participate in a TEM with 10 rivals, including 5 sellers and 5 buyers. The rivals’ offer and bid are given in Table 3. It is clear that they can provide maximum 2MWh in each hour as a seller or buyer.
5.2. Bidding strategy in the TEM

In the following, the numerical results, which are extracted from the proposed model, are given for 4 cases. In Fig. 6, the bidding strategy of the MG in TEM and the commitments of the DAM are shown. The positive and negative values indicate the role of buyer and seller, respectively. In case 1 and 2, the MG sold energy to the DAM one day before. Therefore, the price of DAM was so high that was profitable for MG to employ its DERs to produce energy. After the DAM clearing, the MG deals with net load uncertainty in peak and off-peak duration in case 1 and case 2, respectively. In Fig. 6(a), it is shown that MG should buy energy deficit as much as 1MWh in the TEM during the peak (i.e. case 1). Moreover, it is shown that MG can sell its excess energy in the TEM during the off-peak (i.e. case 2).

In case 3 and 4, the MG bought energy from the DAM one day before. Therefore, the price of DAM was not so high that was profitable for MG to employ its DERs to produce energy. However, after the DAM clearing, the MG faces with the net load uncertainty in peak and off-peak duration in case 3 and case 4, respectively. By the realization of the peak load or off-peak, it can provide its energy deficit by the TEM; see Fig. 6(b).

In Table 4, the pairs of quantity and price \((P^{TEM-buy}, \alpha^{buy})\), which are submitted to the TEM, are given. Moreover, the MCP of TEM is shown in each hour. Regarding the MCP of the TEM, in Table 3, the grey shaded area shows the rejected offers, and the white area shows the accepted bid and offers. In case 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, whose prices are the most expensive price. In case 3, the MG tends to sell energy cheaper than the DAM price in the TEM, instead of selling energy in RTM prices, whose prices are the cheapest price.

5.3. The optimal operation of DERs in the TEM

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

The SOC of the ESS is illustrated in Fig. 7(b). In all cases, the ESS charge during time 1, which is the lowest price in the TEM (see Table 3), and release its energy to MG during time 2 and time 3, when the prices of TEM are at the highest value.

In Fig. 7(c), the DR consumption is illustrated. In the 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 $/MWh), so the DR consume its minimum energy during the entire time horizon. In case 2, the TEM prices in times 1, 3 and 4 are lower than the
95$/MWh, so it consumes more than its minimum capability (i.e. 3MWh). In cases 4 and 5, in all time, 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 participating in the TEM. In Table 5, the profit of the MG is investigated by detail. By the participation in the DAM, the MG earned 886.3 ($) in cases 1 and 2, and paid -733.4 ($) in cases 3 and 4. In case 1, 3 and 4, the term of TEM profit is negative in reason of buying energy in TEM, and its equal to -450.9 ($), -145.0 ($) and -21.9 ($), respectively. In the case 2, which net loads and its uncertainty are at lowest value (see Fig.5 (b)), and the TEM prices are high enough to make the production of DERs profitable, the MG can earn 215.4 ($) from TEM.

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

6. Conclusion
In this paper, the bidding strategy of the MG in the transactive energy market is proposed based on a bi-level optimization with interval coefficient, in which the profit of the MG maximizes in the upper level, and the clearing of the TEM market is considered as the lower level problem. In order to solve the proposed model, the problem recasts as a single level interval optimization by using KKT conditions, and interval optimization concept. In addition, the uncertainty of the net loads is handled by the 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, whose prices are the most expensive price. Also,
- The MG tends to sell energy cheaper than the DAM price in the TEM, instead of selling energy in RTM prices, whose prices are the cheapest price
- By investigating the profitability of the TEM for the MG, it can earn 1.7% more profit from every 4-hour by the participation in the TEM. Consequently, by 24-hour participation in TEM, it can increase its profit to 10.2%.

Future research focuses on the extents of the proposed model to the participation of the MGs in TEM with distribution grid cost allocation.
7. References


Authors’ Biography

Hossein Nezamabadi received his B.Sc. and M.Sc. 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 B.Sc. degree from K. N. Toosi University of Technology, Tehran, Iran, in 2004, and the M.Sc. and Ph.D. degree 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. He has demonstrated a consistent track record of attracting external fund and he has managed several national and international projects and closely worked with several large complex national/international projects. He was considered as one of the Outstanding Reviewers of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, in 2018 and top 1% reviewers in engineering according to Publon’s Peer Review Awards, in 2018. His research interest is oriented to 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 in energy system studies (modeling, forecasting and optimization). Dr Vahidinasab is a senior member of the IEEE, 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.

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### Table 1 Technical and economical characteristics of DGs and RESs

<table>
<thead>
<tr>
<th>Unit</th>
<th>Type</th>
<th>Cost Coefficient ($/MWh)</th>
<th>Min-Max capacity (MW)</th>
<th>Ramp Up/Down Rate (MW/h)</th>
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<tbody>
<tr>
<td>G1</td>
<td>Controllable</td>
<td>27.7</td>
<td>1-5</td>
<td>2.5</td>
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<tr>
<td>G2</td>
<td>Controllable</td>
<td>39.1</td>
<td>1-5</td>
<td>2.5</td>
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<td>G3</td>
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<tr>
<td>G4</td>
<td>Controllable</td>
<td>125.0</td>
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<td>-</td>
</tr>
<tr>
<td>G5</td>
<td>Stochastic</td>
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<td>0-0.5</td>
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</tr>
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<td>G6</td>
<td>Stochastic</td>
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<td>G7</td>
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<td>G8</td>
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### Table 2 Cases assumption

<table>
<thead>
<tr>
<th>Case</th>
<th>DAM Commitment (MWh, $/MWh)</th>
<th>MG Load</th>
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<tbody>
<tr>
<td>Case 1</td>
<td>(1, 86.67)</td>
<td>Peak</td>
</tr>
<tr>
<td>Case 2</td>
<td>(1, 86.67)</td>
<td>Off-peak</td>
</tr>
<tr>
<td>Case 3</td>
<td>(-10.5, 15)</td>
<td>Peak</td>
</tr>
<tr>
<td>Case 4</td>
<td>(-10.5, 15)</td>
<td>Off-peak</td>
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### Table 3 Rivals’ offer and bid in the TEM

<table>
<thead>
<tr>
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<th>Time 1</th>
<th>Time 2</th>
<th>Time 3</th>
<th>Time 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 &amp; Case 2</td>
<td>B1 (1, 107.0)</td>
<td>(1, 152.90)</td>
<td>(1, 149.0)</td>
<td>(1, 126.4)</td>
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<tr>
<td></td>
<td>B2 (0.25, 90.1)</td>
<td>(0.25, 128.8)</td>
<td>(0.25, 125.5)</td>
<td>(0.25, 106.5)</td>
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<tr>
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<td>B3 (0.25, 89.0)</td>
<td>(0.25, 127.2)</td>
<td>(0.25, 123.9)</td>
<td>(0.25, 105.1)</td>
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<tr>
<td></td>
<td>B4 (0.25, 88.4)</td>
<td>(0.25, 126.3)</td>
<td>(0.25, 123.1)</td>
<td>(0.25, 104.1)</td>
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<tr>
<td></td>
<td>B5 (0.25, 87.5)</td>
<td>(0.25, 125.1)</td>
<td>(0.25, 121.9)</td>
<td>(0.25, 103.4)</td>
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<tr>
<td>S1</td>
<td>(1, 10.8)</td>
<td>(1, 11.0)</td>
<td>(1, 11.8)</td>
<td>(1, 10.9)</td>
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<td>S2</td>
<td>(0.25, 11.0)</td>
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<td>S3</td>
<td>(0.25, 11.3)</td>
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<td>(0.25, 13.3)</td>
<td>(0.25, 11.8)</td>
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<td>S5</td>
<td>(0.25, 12.0)</td>
<td>(0.25, 12.8)</td>
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<td>(0.25, 12.3)</td>
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Table 4 The MG offer and bid in the TEM and Market clearing price of the TEM

<table>
<thead>
<tr>
<th>MG role in TEM</th>
<th>Time 1</th>
<th>Time 2</th>
<th>Time 3</th>
<th>Time 4</th>
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<tbody>
<tr>
<td>Case 1 Buyer</td>
<td>((P_{TEM}^{buy}, \alpha_{buy}))</td>
<td>(-1, 90.1)</td>
<td>(-1, 128.8)</td>
<td>(-1, 125.5)</td>
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<td>(\lambda_{TEM})</td>
<td>90.1</td>
<td>128.8</td>
<td>125.5</td>
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<tr>
<td>Case 2 Seller</td>
<td>((P_{TEM}^{buy}, \alpha_{buy}))</td>
<td>(0.75, 78.8)</td>
<td>(0.5, 113.9)</td>
<td>(0.25, 84.462)</td>
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<td>113.9</td>
<td>118.2</td>
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<td>Case 3 buyer</td>
<td>((P_{TEM}^{buy}, \alpha_{buy}))</td>
<td>(-2, 17.8)</td>
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<td>(-2, 18.5)</td>
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<td>(\lambda_{TEM})</td>
<td>17.8</td>
<td>18.2</td>
<td>18.5</td>
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<td>Case 4 buyer</td>
<td>((P_{TEM}^{buy}, \alpha_{buy}))</td>
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<td>17.9</td>
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Table 5 The MG profits

<table>
<thead>
<tr>
<th></th>
<th>DAM profit ($)</th>
<th>TEM Profit ($)</th>
<th>RTM profit ($)</th>
<th>Total profit ($)</th>
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<tbody>
<tr>
<td>Case 1 With TEM</td>
<td>886.3</td>
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<td>-346.2</td>
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<td>Without TEM</td>
<td>-</td>
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<td>-624.4</td>
<td>2075.7</td>
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<td>Case 2 With TEM</td>
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<td>86.2</td>
<td>2611.3</td>
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<td>Without TEM</td>
<td>-</td>
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<td>117.5</td>
<td>2586.6</td>
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<td>Case 3 With TEM</td>
<td>-733.4</td>
<td>-145.0</td>
<td>-134.7</td>
<td>656.5</td>
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<td>Without TEM</td>
<td>-</td>
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<td>-297.2</td>
<td>639.1</td>
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<td>Case 4 With TEM</td>
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