POWER TRADING AND PRICING AMONG DSO AND MULTI-MICROGRID IN TRANSACTIVE ENERGY MARKET

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ABSTRACT

TEM emerges as a new end-to-end power market and enables the synergetic trading and operation of end users. The increasing distributed energy sources (DERs) and microgrids necessitate the synergetic operation and trading. Moreover, due to the business privacy issues, a globally optimized strategy cannot be established effectively. Instead, a paralleled and distributed operation and trading framework gains more scalability and flexibility. An unsolved problem is how to address both coordinated operation and free trading of MMG simultaneously in the TEM. Based on Lagrangian relaxation theory, this paper proposes a synergetic framework and pricing method in which each microgrid is able to trade power with other MGs and DSO while ensuring its own power balance. Case studies shows the established framework achieves good balance between cooperation and autonomy among MMG in the TEM.

INTRODUCTION

As increasing microgrids connect and interact in distribution system, the end-to-end transactive energy (TE) trading and pricing gain more and more concerns. Transactive energy market (TEM) emerges as a new end-to-end power market and enables the energy trading and coordinated operation of end user[1]. The transactive energy applied to electricity grids is to coordinate the power production and consumption of end-users by operation characteristics and economic signals.

Transactive energy trading poses new challenges to distribution system operator (DSO). First, the increasing transactive energy trading could change the operation status significantly and give rise to power losses and congestion problems. Moreover, due to the business privacy of different entities, the DERs information and their impacts on controllable load could be invisible to DSO. A paralleled and distributed operation framework is needed.

In the coordination of multi-microgrid (MMG), reference [2] presented a distributed model predictive control scheme where stochastic energy management and coordination of MMG are addressed. In [3] a two-stage MMG energy exchange strategy is established for to make use of electrical vehicles and limit the power exchange peak. Reference [5] discussed the coordinated design and operation of MMG. In [6] the interaction between MMG and distribution system is modeled by bi-level programming while the interaction among MMG follows interactive energy game process. Reference [7] introduced virtual power plant to coordinate the transactive energy of DERs in the proposed hierarchical scheduling framework. In [8] the transactive energy framework and distribution locational marginal price (DLMP) are proposed where transmission, distribution and MMG are simultaneously addressed. Based on Lagrangian relaxation, [9] presents an optimal operation strategy for MMGs in which Lagrangian multipliers are used as control signals of autonomous microgrids. Reference [10] adopted Lagrangian relaxation to describe the transactive energy trading process among MMG in which Lagrangian multipliers are interpreted as power trading price.

This paper focuses on the power trading mechanism among MMG and DSO in the TEM. Based on Lagrangian relaxation theory, an end-to-end TE trading framework and pricing method are proposed in which each microgrid is able to trade power with other MGs and DSO while ensuring its own power balance.

TRANSACTIVE ENERGY MARKET MODEL

The concept and definition of transactive energy have been proposed in some references[1][11]. According to the Gridwise Architecture Council[11], TE is defined as “A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter”.

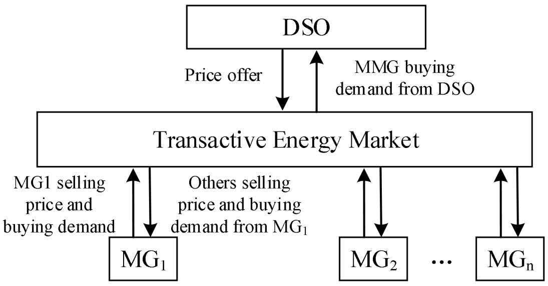

Fig.1 The framework of MMG trading mechanism

In the transactive energy market, DSO and MMG are independent participants with their individual and specific objectives. Each microgrid exchanges its buying demand and selling price with other MGs in the TEM. Based on the buying demand and selling price of other entities, one MG can update its own decision until all MGs do not change their decisions any more. The proposed transactive energy market model is shown in Fig. 1 and described as follows.

- Each MG participated in TEM has one microturbine (MT) and is connected with distribution system. Each MG is responsible for the power balance of itself.
- Each MG can exchange TE with other MGs. The TE price is determined by Lagrangian multipliers.
- Each MG broadcasts its own TE quantity and selling price in the TEM. And each MG update its strategy after receiving other MGs' decisions.
- The purchaser will undertake the delivery cost which is defined in terms of power losses and affected by network topology and purchased power.
- A MG can also exchange TE with DSO. The buying and selling price from DSO is based on the time-of-use (TOU) power price.

Lagrangian Relaxation of MMG

The trading process is modeled by Lagrangian relaxation and each microgrid forms a Lagrangian subproblem. The primal objective function is

$$\min \sum_{t=1}^{NT}\sum_{i=1}^{NMG}\left(C(P_{MT,i}^{t})+\eta_{TOU}^{t}\cdot E_{pur,iD}^{t}+\sum_{j=1}^{NMG}\phi_{ij}(E_{pur,ij}^{t})\right)$$

where the first term $C(P_{MT,i}^{t})$ is the microturbine generation cost and $C(x)=ax^2+bx+c$. The second term is the cost of power purchase from DSO for MG$_i$ where η_{TOU}^{t} and $E_{pur,iD}^{t}$ are the TOU price and power purchase volume from DSO at time *t*, respectively. The third term is the power transfer costs for MG$_i$ if MG$_i$ buys electricity from other microgrids. The third term $\phi_{ij}(E_{pur,ij}^{t})$ is a quadratic function of the transferred power and defined as

$$\phi_{ij}(E_{pur,ij}^{t})=\sum_{j=1}^{NMG}d_{ij}^{t}\cdot {E_{pur,ij}^{t}}^{2}$$

where d_{ij}^{t} is the equivalent distance between microgrid *i* and *j* which is determined by the line resistance between the two microgrid nodes. $E_{pur,ij}^{t}$ is the purchase volume of MG *i* from MG *j*.

The model constraints are shown below. For $\forall i\in MG$

$$P_{MT,i}^{t}+\sum_{j\neq i,j\in MG}E_{pur,ij}^{t}+E_{pur,iD}^{t}-E_{sel,i}^{t}-Pd_{i}^{t}=0$$

$$P_{MT,i}^{\min}\leq P_{MT,i}^{t}\leq P_{MT,i}^{\max}$$

$$E_{pur,ij}^{t}\geq 0,\ E_{pur,ii}^{t}=0,\ E_{pur,iD}^{t}\geq 0,\ E_{sel,i}^{t}\geq 0$$

Constraint is the power balance of MG$_i$ where $P_{MT,i}^{t}$ is the MT generation. Constraint is the upper and lower bound of MT generation. Constraints are the lower bound of trading volume.

The coupling constraints is the selling volume of MG$_i$ equals to the total volume that all other microgrids buying from MG$_i$.

$$E_{sel,i}^{t}=\sum_{j=1}^{NMG}E_{pur,ji}^{t},\ i=1,2,\cdots,NMG$$

Note that once the coupling constraints are decoupled, the MMG problems can be decoupled. Lagrangian relaxation is applied and we get Lagrangian function

$$f(\lambda)=\sum_{t=1}^{NT}\sum_{i=1}^{NMG}(C_i({P_{MT,i}^{t}}^{2})+\sum_{j\in MG}\phi_{ij}(E_{pur,ij}^{t})+\eta_{TOU}^{t}E_{pur,iD}^{t}$$
$$+\lambda_i^t(E_{pur,1i}^{t}+E_{pur,2i}^{t}+...+E_{pur,NMG,i}^{t}-E_{sel,i}^{t}))$$

The relaxed problem can be separated into MG sub-problems, i.e. one subproblem for one microgrid. The objective function of subproblem *i* is

$$\min \sum_{t=1}^{NT}C_i({P_{MT,i}^{t}}^{2})+\sum_{j=1}^{NMG}\phi_{ij}(E_{pur,ij}^{t})+\eta_{TOU}^{t}E_{pur,iD}^{t}+$$
$$\lambda_1^t E_{pur,i1}^{t}+\lambda_2^t E_{pur,i2}^{t}+\cdots+\lambda_{NMG}^{t}E_{pur,i,NMG}^{t}-\lambda_i^t E_{sel,i}^{t}$$

s.t. - for microgrid *i*

The update and interpretation of Lagrangian multipliers

The Lagrangian multipliers are updated by the sub-gradient method which is shown as

$$\lambda_i^t[k+1]=\lambda_i^t[k]+\left(\frac{1}{pk+q}\right)\left(\sum_{j=1}^{NMG}E_{pur,ji}^{t}[k]-E_{sel,i}^{t}[k]\right)$$

where *k* is the iterations.

In we can see that when $\sum_{j=1}^{NMG}E_{pur,ji}^{t}>E_{sel,i}^{t}$, i.e. the total power demand buying from MG$_i$ exceeds MG$_i$'s supply, λ_i[k+1] will get larger comparing with λ_i[k]. On the other hand, when $\sum_{j=1}^{NMG}E_{pur,ji}^{t}<E_{sel,i}^{t}$, i.e. the supply of MGi exceeds total buying demand, λ_i[k+1] will decrease. When $\sum_{j=1}^{NMG}E_{pur,ji}^{t}=E_{sel,i}^{t}$, λ_i[k+1] will remain the same as λ_i[k].

The change in value of λ_i depends on the difference between the total buying demands of other microgrids and MG$_i$ own sales demand. The variation trend is also followed by the market price, i.e. in the buyer market the price will be lower, while in the seller market the price will be higher. This indicates that the Lagrangian multipliers provide a good signal on the electricity pricing in transactive energy trading process. Moreover, if the multiplier λ_i is viewed as the selling price of MG$_i$, the second line of denotes the MG$_i$ purchase cost from other microgrids (purchase volume multiplied by the corresponding price offer) minus the MG$_i$ income at the price offer λ_i and sold quantity $E_{sel,i}^{t}$. In this way, the purchase cost and sales revenue are added automatically into the self-decision of each microgrid.

PROPOSED TE MARKET INTERACTION AND TRADING PROCESS

The information interaction and trading process is shown in Fig. 2 and described as follows.

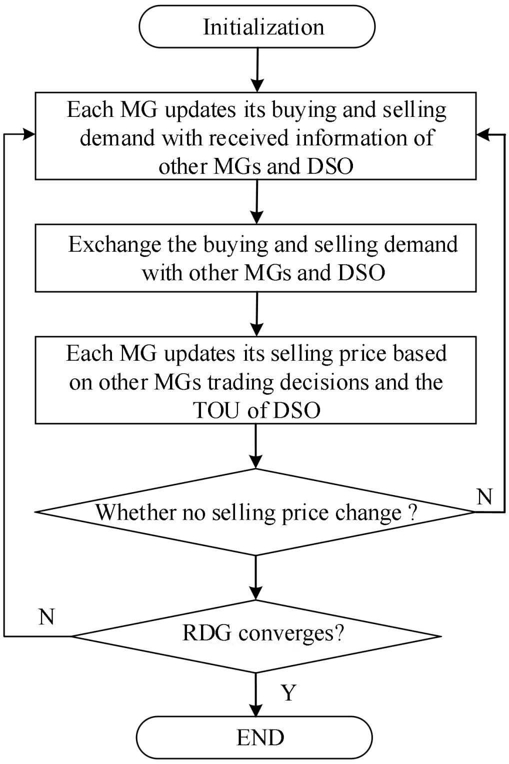

Fig. 2 The information interaction and trading process

1) Initialize required parameters, such as network topology, MT cost curve, TOU price, system load, etc. Form the Lagrangian relaxation problem .
2) Each microgrid solves its own Lagrangian subproblem based on the received selling price of other MGs, i.e. Lagrangian multipliers **λ**, and the TOU price of DSO. MG$_i$ buying demand $E^t_{pur,ij}$, j=1,2,…,NMG, are updated in this step.
3) Each microgrid broadcasts its own buying demand to all the participants in the TEM. Meanwhile, each microgrid receive the demand that other MGs buying from them.
4) Based on the total buying demand of other participants, MGi will update its selling price according to in the TEM. Mathematically, the price change process is known as Lagranian multipliers update.
5) If the all the MGs' selling price (Lagrangian multipliers) do not change comparing with the last iteration, calculate the relative duality gap (RDG). Otherwise each microgrid broadcasts its latest selling price to other MGs and receives their selling price. Then go back to step 2).
6) If the convergence condition of RDG is satisfied, Submit the final trading results to TEM. Otherwise go back to step 2).

CASE STUDIES

To show the effectiveness of the proposed transactive energy trading mechanism, one case study is considered. One simple 4-bus distribution system with two microgrids are considered. To focus on the detailed trading results and marginal cost analysis, only one-hour horizon is shown in the case study.

The 4-bus system topology is shown Fig. 3. The branch 4 is a tie switch. The system data are shown in Table 1 and Table 2. The TOU price is 0.3 \$/kWh.

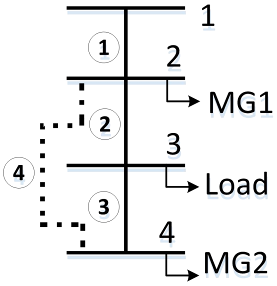

Fig. 3 4-bus distribution system

Table 1 The 4-bus system data

Bus	Branch			Load at Bus i	
	Bus	R	X	P(kW)	Q(kVar)
1	1-2	0.0575	0.0293	0	0
2	2-3	0.3076	0.1567	100	60
3	3-4	0.2284	0.1163	90	40
4	2-4	0.2378	0.1211	80	30

Table 2 The MT parameters in each MG

	a	b	c	P_{min} (kW)	P_{max} (kW)
MT1	0.0005	0.1809	1.223	0	150
MT2	0.002	0.1609	1.100	0	120

The following scenarios are considered in the case study.

Scenario 1: MMG generate but neither sell nor buy.

Scenario 2: MMG generate and trade with each other, but never trade with DSO.

Scenario 3: Each MG generate and trade with each other. MMG can also choose to buy from DSO.

Scenario 4: Based on Scenario 3, the network topology is changed.

In Scenario 1, two small MGs supply the local load by their own MT and without trading. Scenario 1 leads to the largest total cost \$51.085.

In scenario 2, MMG can trade with each other, but DSO doesn't participate the TEM. Each MG supplies its load by local MT generation and trading TE with each other. The simulation results are shown in Table 3. MG2 buy 20.881 kWh from MG1 at the price $\lambda_1 = 0.319$ \$/kWh. The TE coordination leads to lower total cost \$47.289. Note that the price λ_1 is higher than TOU price due to MT marginal cost and TE delivery cost.

In scenario 3, DSO is considered as a participant of TEM. The simulation results are shown in Table 4. The MG2 not only buys from MG1, but also buys from DSO to maximize its own profits. The total cost is further reduced to \$46.936 compared with that in Scenario 2.

Table 3 Simulation results in Scenario 2

MMG Trading Behavior (kWh)		$\begin{pmatrix}\lambda_1\\ \lambda_2\end{pmatrix}$	MMG Cost (\$)	
Buying	Selling		MG1	MG2
E_{pur21}=37.965	$E_{sel,1}$=37.965	0.319 0.279	23.592	23.696

Table 4 Simulation results in Scenario 3

MMG Trading Behavior (kWh)		$\begin{pmatrix}\lambda_1\\ \lambda_2\end{pmatrix}$	MMG Cost (\$)	
Buying	Selling		MG1	MG2
E_{pur21}=17.398 E_{pur2D}=27.087	$E_{sel,1}$=17.398	0.297 0.300	24.162	22.774

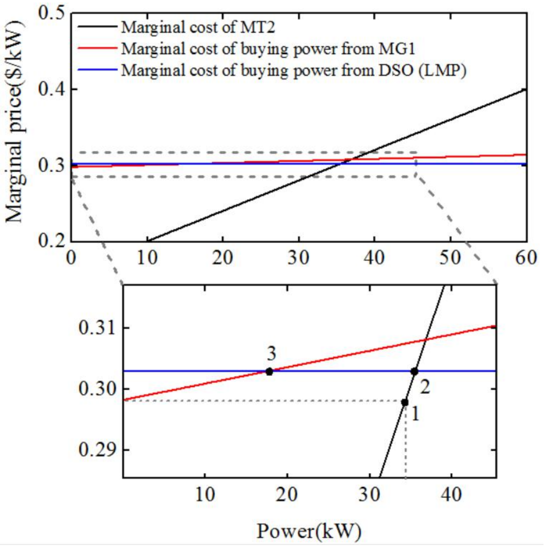

Fig. 4 The marginal cost of MG2

The trading behavior of MG2 can be interpreted in terms of marginal cost as shown in Fig. 4. When the MT2 is dispatched at 34.275kW, as shown in the Fig. 10 point 1, the marginal cost of MT2 is 0.297\$/kW which is the same as the price for buying power from MG1. Then, MG2 will increase the dispatch of MT2 as the load increases and buy power from MG1 until MT2 reaches 35.515kW (point 2) and the purchase from MG1 reaches 17.398kW (point 3). In this case, the marginal cost of MT2, as it purchases from MG1, is equal to the marginal cost of power purchase from DSO, i.e. TOU 0.3\$/kWh. Finally, if the load is higher than 35.515 + 17.398 = 52.913kW, MG3 will choose to buy from DSO to supply the rest part of load which is 27.087kWh in this case.

In Scenario 4, the network topology changes. Since the delivery cost of TE is impacted by electrical distance, the network topology will affect the trading behaviors. The switch of branch 2 is opened and the tie line is connected. The trading results is shown in Table 5. We can see that the total cost is \$40.851 in Scenario 4 which is lower than that in Scenario 3. Therefore, rational network topology could not only reduce power losses, but also the MMG costs. This observation indicates that different position of MMG and network topology could impact the trading behaviors significantly. This conclusion should be considered in the operation and design of MMG.

Table 5 Simulation results in Scenario 4

MMG Trading Behavior (kWh)		$\begin{pmatrix}\lambda_1\\ \lambda_2\end{pmatrix}$	MMG Cost (\$)	
Buying	Selling		MG1	MG2
E_{pur21}=19.716 E_{pur2D}=4.769	$E_{sel,1}$=19.716	0.298 0.273	24.119	16.732

CONCLUSION

This paper proposes a TE trading mechanism for MMG connected with distribution system. The Lagrangian relaxation method can be used to model the distributed and paralleled trading between DSO and MMG and among MMGs. Lagrangian multipliers provide an effective price signal in TEM. MMG's trading behavior is affected significantly by the distribution network topology and MMG connection node, which should be considered when operating and designing MMG system.

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