International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 157

Transmission System Operator-Distribution System Operator coordination for integrated flexibility market

Tao Jiang[1], Zhongwei Shen[1], Xiaolong Jin[2*], Xue Li[1], Rufeng Zhang[1], Houhe Chen[1]

[1] Department of Electrical Engineering, Northeast Electric Power University, Jilin 132012, China

[2] Center for Electric Power and Energy (CEE), Department of Electrical Engineering, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark

ABSTRACT

With high penetration of distributed generations (DGs), distribution networks are becoming more and more 'active'. Active distribution networks (ADNs) provide the opportunity of providing flexibility for the transmission system operator (TSO) through a flexibility trading platform. To provide such a trading platform, a TSO-DSO coordinated flexibility market is proposed in this paper. To clear the market while protecting the privacy of TSO and DSO, an ADMM-based market clearing solution is proposed. Case studies are conducted on the testing system of the IEEE 30-bus transmission network with two 33-node ADNs. Numerical studies demonstrate the proposed flexibility market framework can reduce the total flexibility cost of the TSO. Besides, the economic benefits of ADNs can also be improved.

Keywords: ADMM, distributed energy resources, flexibility market, TSO-DSO coordination

NONMENCLATURE

Abbreviations	
ADMM	Alternating direction method of multipliers
DG	Distributed generator
DSO	Distribution system operator
TSO	Transmission system operator
Symbols	
l	Index of lines of transmission network
b	Index of load nodes of transmission grid
h	Index of generator nodes of transmission grid
g	Index of DG nodes of ADN
e	Index of transmission network buses connected to ADN
ij	Index of branches of ADN
a	Index of ADN
$y1(j)/y2(j)$	Set of the initial/terminal node of line with terminal/ initial node j in ADN
G	Set of generators at the transmission level
PCC	Set of coupling nodes
L	Set of loads at the transmission level
NA	Number of ADN
A	Set of DGs in the ADN
$C_{h,t}^{Gen,fle}$	Genco's offer to provide flexibility (\$/MWh) at time t
π_t^{FM}	DSO's offer to provide flexibility at time t
$C_{g,t}^{DG,fle}$	Cost of DG (\$/MWh) at time t
$\Delta P_{h,t}^{G}$	Generator's output to provide flexibility at time t
$P_{h,t}^{G}$	Generator's output in energy market at time t
$P_{e,t}^{flein}$	The amount of flexibility purchased from DSO at time t
$P_{e,t}^{sell}$	Electricity delivered by the transmission grid to the distribution grid at time t
$D_{b,t}$	Net load of transmission network
$\Delta D_{b,t}$	Change of net load of transmission network
$ramp_h$	Ramp rate of a generator (MW/15min)
$P_{h,\min}^{G}/P_{h,\max}^{G}$	Minimum/Maximum generation output of generator
$RateA_{l,\min}/RateA_{l,\max}$	Minimum/Maximum flow capacity of transmission line l
GSF	Generation shift factor
$p_t^{Dis,fle}$	The amount of flexibility delivered to TSO by DSO at time t
$\Delta P_{g,t}^{DG}$	Active power output of DGs to provide flexibility at time t
$p_{j,t}^{d}/q_{j,t}^{d}$	Active/Reactive load of node j in ADN at time t
$p_{g,t,min}^{DG}/p_{g,t,max}^{DG}$	DGs' minimum/maximum active power output at time t
$I_{ij,t}$	Square of the current on line ij at time t in ADN
$U_{i,t}$	Square of voltage on node j at time t in ADN

1. INTRODUCTION

Flexibility requirements come from the increasing renewable generation, which brings larger uncertainty and variability to the net load. Usually, flexibility is defined as the possibility of modifying generation and/or consumption patterns in response to an external signal (activation or price signals) to cost-effectively promote stability of the power system [1].

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

So far, only traditional generators (e.g., thermal and hydropower units) are eligible sources for providing flexibility in most electricity markets. However, the increasing uncertainty and variability are making it more difficult to balance generation and load [2], moreover, conventional generators don't have enough ramping capability in most conditions. Actually, any dispatchable resource (e.g., distributed generations (DGs)) may provide flexibility with an economic energy bid [3].

However, the flexibility of ADN has not been fully utilized to TSO, the related framworks and models are less studied. This promotes the need for new flexibility market design to facilitate flexibility trading between the TSO and the DSO. Thus, coordination between TSO and DSO becomes critical so that the flexibility services offered to the TSO do not cause other problems to the DSO.

In view of the above, this paper proposes a TSO-DSO coordinated flexibility market clearing model, where DSO sells flexibility and TSO buys flexibility in the market. In order to protect the privacy of data, an ADMM-based algorithm is used to clear the market.

2. PROBLEM STATEMENT

Since DSO is the owner of the DGs, it has the capability of providing flexibility to participate in the flexibility market together with Generation companies (Gencos) ,which is showed in Fig. 1. In the proposed framework, the TSO firstly sends a flexibility request to the flexibility market operator(FMO), which collects flexibility bids from Gencos and DSOs and then conduct market clearing to minimize the total cost of buying flexibility. Finally, the market clearing results are sent back to the TSO.

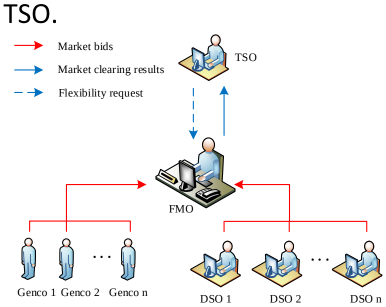

Fig.1 Framework of the integrated flexibility market

3. MATHEMATICAL MODELING

3.1 TSO-DSO coordination

To reduce the amount of information exchange between regions and protect the privacy of data, the general form of consensus optimization method of ADMM is introduced.

Take the testing system (node 4 of the transmission network is replaced by the 7-node ADN) in Fig. 2 as an example. The system is divided into two subareas by cutting the tie lines between the transmission and distribution network. The coupled variable value is obtained after optimizing each subarea. The updated global variable is the average value of the coupled variable connected to it, which is sent back to each sub-area to participate in the next optimization. Loop the optimization within the area and the information exchange between the subareas in Fig. 2 until the variables meet the ADMM convergence condition. And if the values of the coupling variables are equal when the iteration stops, the decoupling process is considered successful.

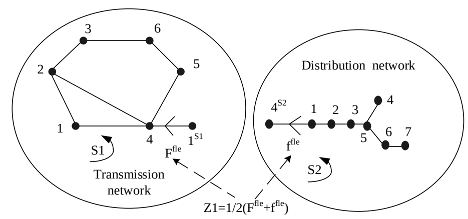

Fig.2 Regional independent optimization and information interaction process

3.2 Distribution network-level model

In the distribution network-level model, DSO conducts the optimization with maximum social welfare. The first term is the profit of the DSO from flexibility trading. And its cost of providing flexibility is modeled in the second term. The optimization model is formulated as below,

$$\max \sum_{a=1}^{NA}\left(\pi_{a,t}^{FM} p_{a,t}^{Dis,fle} - \sum_{g\in A} C_{g,a,t}^{DG,fle} \Delta p_{g,a,t}^{DG}\right) \tag{1}$$

$$\begin{aligned} s.t. \sum_{i\in y1(j)} p_{ij,a,t} - I_{ij,a,t} r_{ij,a} - \sum_{k\in y2(j)} p_{jk,a,t} \\ + \left(p_{g,a,t}^{DG} + \Delta p_{g,a,t}^{DG}\right) - p_{j,a,t}^{d} = 0, \forall j \end{aligned} \tag{2}$$

$$\begin{aligned} \sum_{i\in y1(j)} q_{ij,a,t} - I_{ij,a,t} x_{ij,a,t} - \sum_{k\in y2(j)} q_{jk,a,t} \\ + \left(q_{g,a,t}^{DG} + \Delta q_{g,a,t}^{DG}\right) - q_{j,a,t}^{d} = 0, \forall j \end{aligned} \tag{3}$$

$$\begin{aligned} U_{j,a,t} = U_{i,a,t} - 2(r_{ij,a,t} p_{ij,a,t} + x_{ij,a,t} q_{ij,a,t}) \\ + ((r_{ij,a})^2 + (x_{ij,a,t})^2) I_{ij,a,t}, \forall ij \end{aligned} \tag{4}$$

$$\left\| \begin{matrix} 2p_{ij,a,t} \\ 2q_{ij,a,t} \\ I_{ij,a,t} - U_{i,a,t} \end{matrix} \right\|_2 \le I_{ij,a,t} + U_{i,a,t}, \forall ij \tag{5}$$

$$0 \le p_{a,t}^{Dis,fle} \tag{6}$$

$$\sum_{a=1}^{NA} p_{a,t}^{Dis,fle} \le FLE_t^{sys} \tag{7}$$

$$\left(V_{i,a,\min}\right)^2 \le U_{i,a,t} \le \left(V_{i,a,\max}\right)^2, \forall i \tag{8}$$

$$0 \le \Delta p_{g,a,t}^{DG}, \forall g \tag{9}$$

$$p_{g,a,t,\min}^{DG} \le p_{g,a,t}^{DG} + \Delta p_{g,a,t}^{DG} \le p_{g,a,t,\max}^{DG}, \forall g \tag{10}$$

$$q_{g,a,t,\min}^{DG} \le q_{g,a,t}^{DG} + \Delta q_{g,a,t}^{DG} \le q_{g,a,t,\max}^{DG}, \forall g \tag{11}$$

Constraints (2) and (3) are the nodal active and reactive power balance equations after providing flexibility, respectively. Constraint (4) is the voltage drop equation. The line flow limit after SOC relaxation is modeled in (5). The sum of the flexibility provided by each DSO cannot exceed the flexibility demand value, which is described in (7). The nodal voltage constraint is modeled in (8). Constraints (10) and (11) describe DGs' active and reactive power output limits.

3.3 Transmission network-level model

After flexibility bidding process, the flexibility market is cleared to meet the TSO's flexibility needs with the objective of minizing flexibility procurement cost. The formula for the market clearing problem is as follows,

$$\min \sum_{h\in G} C_{h,t}^{Gen,fle} \cdot \Delta P_{h,t}^{G} + \sum_{a=1}^{NA} \sum_{e\in PCC} \pi_{a,t}^{FM} P_{e,t}^{flein} \tag{12}$$

$$\begin{aligned} s.t. \sum_{h\in G}\left(\Delta P_{h,t}^{G} + P_{h,t}^{G}\right) - \sum_{e\in PCC} P_{e,t}^{sell} \\ -\sum_{b\in L}\left(D_{b,t} + \Delta D_{b,t}\right) + \sum_{e\in PCC} P_{e,t}^{flein} = 0 \end{aligned} \tag{13}$$

$$\sum_{e\in PCC} P_{e,t}^{flein} + \sum_{h\in G} \Delta P_{h,t}^{G} = FLE_t^{sys} \tag{14}$$

$$0 \le P_{e,t}^{flein}, \forall e \tag{15}$$

$$-ramp_h \le \Delta P_{h,t}^{G} \le ramp_h, \forall h \tag{16}$$

$$P_{h,\min}^{G} \le P_{h,t}^{G} + \Delta P_{h,t}^{G} \le P_{h,\max}^{G}, \forall h \tag{17}$$

$$\begin{aligned} RateA_{l,\min} \le \sum_{h\in G} GSF_{l\text{-h}} \cdot (\Delta P_{h,t}^{G} + P_{h,t}^{G}) \\ -\sum_{b\in L} GSF_{l\text{-b}} \cdot (D_{b,t} + \Delta D_{b,t}) - \sum_{e\in PCC} GSF_{l-e} \cdot P_{e,t}^{sell} \\ + \sum_{e\in PCC} GSF_{l-e} \cdot P_{e,t}^{flein} \le RateA_{l,\max}, \forall l \end{aligned} \tag{18}$$

Constraint (13) is the power balance equation of transmission network after providing flexibility. Eq. (14) represents the flexibility balance equation, where the flexibility is supplied by DSOs and Gencos. The ramp limit of the generator is modeled in (16). Constraint (17) represents the output limit of each generator. Capacity limits of each transmission line is modeled in (18).

3.4 The ADMM-based market clearing strategy

In this section, an ADMM-based market clearing strategy is proposed. Since the market clearing problem in (1)-(18) is formulated as a convex model, the convergence of the ADMM-based algorithm is guaranteed [4].

The augmented Lagrangian is formulated as below,

$$\begin{aligned} \max \sum_{a=1}^{NA}\Bigg(\pi_{a,t}^{FM} p_{a,t}^{Dis,fle} - \sum_{g\in A} C_{g,a,t}^{DG,fle} \Delta p_{g,a,t}^{DG} \\ + \lambda_{m,t}^{T}\left(p_{a,t}^{Dis,fle} - Z_{a,t}\right) + (\rho/2)\left\| p_{a,t}^{Dis,fle} - \right\|_2^2 \Bigg) \end{aligned}$$

Subject to: (2)-(11)

$$\begin{aligned} \min \sum_{h\in G} C_{h,t}^{Gen,fle} \cdot \Delta P_{h,t}^{G} + \sum_{a=1}^{NA} \sum_{e\in PCC} \pi_{a,t}^{FM} P_{e,t}^{flein} \\ + \lambda_{n,t}^{T}\left(P_{e,t}^{flein} - Z_{a,t}\right) + (\rho/2)\left\| P_{e,t}^{flein} - Z_{a,t} \right\|_2^2 \end{aligned}$$

Subject to: (13)-(18)

After solving the above problems, the variables are updated in the following way:

$$Z_{a,t}^{k+1} = (1/2)\cdot\left(p_{a,t}^{Dis,fle,(k+1)} + P_{e,t}^{flein,(k+1)}\right) \tag{19}$$

$$\lambda_m^{k+1} = \lambda_m^{k} + \rho\left(p_{a,t}^{Dis,fle,(k+1)} - Z_{a,t}^{k+1}\right) \tag{20}$$

$$\lambda_n^{k+1} = \lambda_n^{k} + \rho\left(P_{e,t}^{flein,(k+1)} - Z_{a,t}^{k+1}\right) \tag{21}$$

Eq. (19) is the update of global variables, and the Lagrangian multiplier is updated through (20)-(21). After updating the variables, the convergence of ADMM is judged by (22). The convergence thresholds of the dual residual ε_1、ε_2 and primal residual ε_3 are set as 10^{-5}.

$$\begin{cases} \left\| r_m^{k+1} \right\|_2^2 = \left\| p_{a,t}^{Dis,fle,(k+1)} - Z_{a,t}^{k+1} \right\|_2^2 \le \varepsilon_1 \\ \left\| r_n^{k+1} \right\|_2^2 = \left\| P_{e,t}^{flein,(k+1)} - Z_{a,t}^{k+1} \right\|_2^2 \le \varepsilon_2 \\ \left\| s^{k+1} \right\|_2^2 = \left\| (-\rho)\left(Z_{a,t}^{k+1} - Z_{a,t}^{k}\right) \right\|_2^2 \le \varepsilon_3 \end{cases} \tag{22}$$

4. CASE STUDIES

Case studies were conducted on the testing system of the IEEE 30-bus transmission network with two 33-node ADNs to verify the rationality of the proposed model. There are two wind turbines DG1 and DG2, a photovoltaic source DG3 and two fossil-fuel based DG4 and DG5 in each ADN.

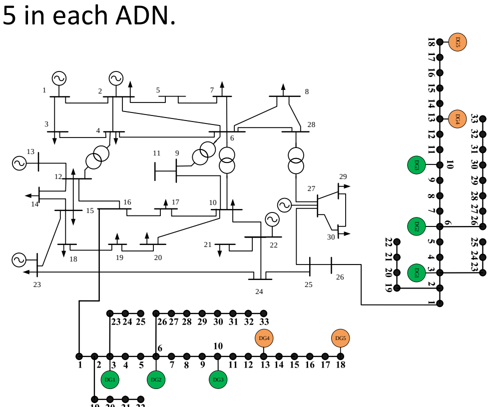

Fig.3 30-bus test system with two active distribution grids

To obtain the baseline energy schedules, we first calculate the optimal power flow for the transmission and distribution network. The goal is to minimize operating costs while meeting operational constraints. Then, the results are used as the inputs to the flexibility market.

In the flexibility market, we assume that the TSO requires upward flexibility of 10 MW, with load node 7 requiring 3 MW, node 21 requiring 4 MW and node 30 requiring 3 MW. Basic data of the system are given in Tab.1 to Tab.3.

Tab.1 The data of Gencos

Genco No.	Maximum output (MW)	Ramp rate (MW/15 min)	Flexibility bidding price ($/MWh)	Output in energy market (MW)
#1	80	6	35	9.34
#2	70	3	30	70
#3	50	2	25	50
#4	55	2	20	55
#5	30	9	46	0
#6	40	9	47	0

Tab.2 The data of DGs in ADN1

DG No.	DG1	DG2	DG3	DG4	DG5
$p^{DG}_{g,t,max}$ (MW)	1	1	1	6	9
$P^{G}_{h,t}$ (MW)	1	1	1	0	0
Flexibility bid ($)	40				

Tab.3 The data of DGs in ADN2

DG No.	DG1	DG2	DG3	DG4	DG5
$p^{DG}_{g,t,max}$ (MW)	0.8	0.8	0.8	7	10
$P^{G}_{h,t}$ (MW)	0.8	0.8	0.8	0	0
Flexibility bid ($)	45				

The flexibility market clearing results are presented in Tab.4 to Tab.6.

Tab.4 Results of flexibility provided by Gencos

Genco No.	#1	#2	#3	#4	#5	#6
$\Delta P^{G}_{h,t}$ (MW)	4.47	0	0	0	0	0

Tab.5 Results of flexibility provided by ADN1

$p^{Dis,fle}_{t}$ (MW)	DG1	DG2	DG3	DG4	DG5
2.72	0	0	0	3.05	0

Tab.6 Results of flexibility provided by ADN2

$p^{Dis,fle}_{t}$ (MW)	DG1	DG2	DG3	DG4	DG5
2.81	0	0	0	3.1	0

The iteration process of the objective value is shown in Fig. 4. After 117 iterations, the ADMM-based algorithm can reproduce the centralized solution. The convergence curves of dual residual and primal residual are presented in Fig. 5.

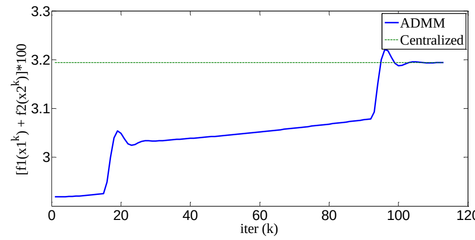

Fig.4 Convergence of the objective value

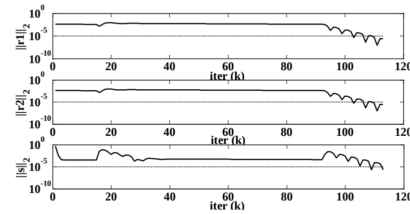

Fig.5 Convergence curves of dual residual and primal residual

As can be observed from Tab. 1, Genco 1 cannot provide all the flexibility by ramping up. Therefore, with the traditional method that only Gencos can participate, the remaining flexibility can only be made up by starting the Genco 5 with high prices. It is obvious that by taking advantage of the flexibility provided by DGs of ADNs, the total cost of purchasing flexibility is significantly reduced.

5. CONCLUSION

In this paper, a TSO-DSO coordinated flexibility market clearing model is proposed. To protect the privacy of data, an ADMM-based algorithm is used to solve the model. For this purpose, the TSO-DSO system is divided into two subareas by cutting the tie lines between transmission and distribution network. TSO and DSO clears the market with transmission and distribution network operation constraints respected. Besides, key network parameters will not be disclosed to FMO.

The proposed market clearing approach can reduce the flexibility cost of the TSO and enhance the competitiveness of Gencos and DGs in ADNs. Besides, the economic benefits of ADNs can also be enhanced.

REFERENCE

[1] Xiaolong Jin, Qiuwei Wu, Hongjie Jia. Local flexibility markets: Literature review on concepts, models and clearing methods. Applied Energy, 2018; 154: 329–340.

[2] N. Navid, G. Rosenwald, Ramp Capability Product Design for MISO Markets, 2013, July.

[3] L. Xu, D. Tretheway: Flexible ramping products, CAISO, December 2014.

[4] Boyd S, Parikh N, Chu E, Peleato B, Eckstein J. Distributed optimization and statistical learning via the alternating direction method of multipliers. Found Trends Mach Learn, 2010; 3(1): 1–122.