A Flow-based Distributed Trading Mechanism in Regional Electricity Market with Energy Hub

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Abstract—The concept of the energy hub (EH) has been emerged to accommodate renewable energy sources in a multi-energy system to deploy the synergies between electricity and other energy sources. However, the market mechanisms for integration of the EHs into the energy markets are not sufficiently elaborated. This paper proposes a flow-based distributed trading mechanism in the regional electricity market (REM) with EH. The regional system operator (RSO) coordinates the net transactions of the regional transmission system in two markets, i.e., a REM market integrated with an EH and the wholesale electricity market of the upstream grid. As an independent stakeholder, each nodal agent uses price disparity to achieve cross-arbitrage from both markets. The EH is a third player intending to maximize his profit from trading in the REM and the wholesale natural gas market. We develop a distributed algorithm based on the alternating direction method of multipliers (ADMM) to obtain the equilibrium solution. The DC power flow is decomposed into optimization problems for the RSO and the agents at different nodes, which can be solved in a distributed manner to achieve the global optimality without violating the privacy of agents. A case study based on a realistic regional transmission system verifies the effectiveness of the proposed mechanism and shows that the mechanism is effective in the decomposition of power flow and the increment of energy efficiency.

Index Terms—electricity market, energy hub, decentralized optimization, electric network constraints.

I. INTRODUCTION

The sustainable development of human society is restricted by climate change and energy shortages [1]. Many countries are encouraging the utilization of renewable energy sources while promoting multi-energy coupling. From a technical perspective, the concept of the energy hub (EH) has been emerged to accommodate renewable energy sources in a multi-energy system to deploy the synergies between electric power and other energy carriers [2]. From a market perspective, the establishment of EHs and distributed energy sources requires an efficient trading mechanism in the regional electricity markets (REMs).

To adapt to the development of distributed energy sources and multi-energy coupling, Li et al. [3] proposed a Lyapunov-based energy management method to achieve economic operation among EHs. An electricity-heat retail market framework was established in [4] to realize the optimal energy allocation of energy station devices. A comprehensive optimal bidding strategy for an EH was modeled in [5], which enabled the EH to benefit from day-ahead and real-time markets. In short, the previous studies, which profound techniques for performing trading mechanisms in a centralized manner, do not consider the important point that every stakeholder has a sense of privacy information protection to reveal their true cost or value functions [6]. To address this point, we need a distributed algorithm for the implementation of the trading mechanisms. While emerging communication and distributed algorithms are also being applied to market bidding [7], it is challenging to implement bidding and power flow calculations in a distributed manner. A bilevel integrated energy sharing mechanism with the decoupled network was designed in [8] for EHs and prosumers, in which it did not consider the limitations of information sharing.

To face the dilemma of information sharing limitations and implementation of power flow constraints, this paper proposes a flow-based distributed trading mechanism for a REM, in which distributed energy sources and EH are independent agents, and they are incentivized to participate in the regional market. The EH is an independent market participant, managing the distributed energy sources, energy storages, and combined heat and power plants, selling and buying electricity from nodal agents to maximize profit. Furthermore, the nodal agents are divided into supplier and consumer nodal agents, which as different stakeholders will only pursue the maximization of their interests. The regional system operator (RSO) plays the role of a selfless auctioneer, intending to clear the REM while achieving cross-arbitrage by trading with EH and the upstream grid. A distributed iterative algorithm based on the alternating direction method of multipliers (ADMM) is developed to implement the proposed mechanism. A case study based on a realistic regional transmission system verifies the effectiveness of proposed algorithm and shows that the proposed mechanism is effective in improving energy efficiency and reducing transaction costs.

The remainder of this paper is structured as follows: Section II presents the proposed trading mechanism framework. In
Section III, the flow-based distributed trading mechanism is proposed. The solution algorithm is proposed in Section IV. A case study is given in Section V, followed by the conclusions in Section VI.

II. FRAMEWORK OF FLOW-BASED DISTRIBUTED TRADING MECHANISM

The flow-based distributed trading market framework is divided into EH and regional transmission-level, which combines consumer nodal agents, supplier nodal agents, and RSO, as shown in Fig. 1. The agents in this market trading mechanism consist of an EH, RSO, consumer nodal agents $C_j$, and supplier nodal agents $S_i$. In the regional transmission system, the RSO as a coordinator, is trading with EH and the upstream grid while performing DC power flow calculations to clear the REM (i.e., to find the intersection of offers from suppliers and consumers).

![Flow-based distributed trading mechanism](image)

**Figure 1.** Structure of flow-based distributed trading mechanism for REM.

The nodes $n \in \mathbb{N} = \{1, \ldots, N\}$ in the regional transmission system, are divided into consumer nodes $j \in \mathbb{J} = \{1, \ldots, J\}$ and supplier nodes $i \in \mathbb{I} = \{1, \ldots, I\}$, particularly $\mathbb{J} \cup \mathbb{I} = \mathbb{N}$. Different rational nodal agents compete with other stakeholders to maximize their own profits, while sharing as little private information as possible, such as cost and value functions. The proposed flow-based distributed trading mechanism, where the agents only share voltage angle $\theta$ as market information, enables clearing the electricity market while implementing DC power flow in a distributed manner. Instead of using simple active power bids, players cannot deduce each other’s cost and value functions from the shared voltage angle information. The regional transmission system is composed of the RSO and all nodal agents as entire stakeholders, with cross- arbitrage from the upstream grid and the EH to derive maximum profit. In terms of the EH, it contains energy conversion and storage facilities together, say, a combined heat and power (CHP) plant, electrical power and electricity storage units. EH, as the third party with the ability to buy and sell electrical energy in the regional market and purchase gas in the wholesale market, can set power prices $\lambda_{b,n}^h$ based on trading power $P_{b,n}^h$ with regional grid and gas price $\lambda_{gas}$ in order to maximize the profit.

III. DECOMPOSED DC FLOW OPTIMIZATION MODEL

The centralized trading model is formulated as an optimization problem presented in (1), which includes DC power flow constraints. They are decomposed by a set of distributed optimization problems (2)-(5). Each stakeholder solves its dedicated problem linked to other problems through some coupling variables and power flow equations as the coupling constraint. The problems of supplier nodal agents, consumer nodal agents, and EH are formulated as in (2), (3), and (4) respectively. The dedicated problem for the RSO as the main coordinator of the proposed distributed mechanism is given in (5). Note that the proposed distributed power flow calculation of each nodal agent in the regional transmission system only needs to share a limited amount of information (voltage angle $\theta_n$). The coupling variables of different nodes are $[P_{n,m}^l, \theta_n]$. The RSO, as a selfless coordinator, first, aggregates market information, then coordinates, estimates, and publishes the market information for the next iteration. It will take several iterations until the convergence condition is met.

A. Centralized Problem

From a centralized perspective, the regional system trades with the EH and the upstream grid, while RSO performs the DC power flow calculations. The centralized problem is to maximize the profit as given in (1).

$$\min_{\substack{P_{n,g}^l, P_{n,g}^b, P_{n,d}^l, P_{n,d}^b, \theta_n \in \mathbb{R} \cup \mathbb{J} \cup \mathbb{I} \cup \mathbb{N} \in \mathbb{R}}} \sum_{n \in \mathbb{N}} \left( c_n(P_{n,g}) - v_n(P_{n,d}) - \lambda_{n,g}^h \sigma_n^h + \lambda_{n,d}^b \sigma_n^b \right)$$

subject to:

1. **Price Constraints**
   $$P_{n,g}^l \leq P_{n,g}^b \leq P_{n,g}^b, \quad P_{n,d}^l \leq P_{n,d}^b = P_{n,d}^b, \forall n$$

2. **Power Flow Constraints**
   $$P_{a,n}^l + \sigma_{a,n}^b = P_{b,n}^l + \sigma_{b,n}^a, \forall m \in \mathbb{R}, m \neq n$$

3. **Voltage Angle Constraints**
   $$\theta_n \leq \theta_n^\max, \forall n$$

4. **EH Prices**
   $$\lambda_{n,g}^h, \lambda_{n,d}^b$$

5. **GH Prices**
   $$P_{b,n}^h, P_{h,n}^b$$

where $c_n(.)$ is the cost function of electricity generation; $v_n(.)$ is the value function of electricity demand; $P_{n,g}^l, P_{n,d}^b$ are the electricity generation and demand at node $n$; $\sigma_n^h, \sigma_n^a$ are the electricity prices from upstream grid and sold to the upstream grid; $\lambda_{n,g}^h, \lambda_{n,d}^b$ are the wholesale market prices of coupling with upstream energy, i.e., electricity and nature gas trading $\sigma_n^h, \sigma_n^a$; and $B_{n,m}$ is the susceptance of line $nm$. Note that the EH prices $\lambda_{n,h}^h, \lambda_{b,n}^b$ are coupled with $P_{b,n}^h, P_{b,n}^h$.

The objective function contains cost of electricity generation, the value of electricity demand, and trading revenue. Constraint (1b) denotes the electricity generation and demand constraints for the node $n$. Constraints (1c) - (1f) are the DC power flow model. Constraint (1c) represents the power balance. Constraint (1d) calculates the active power flow through the transmission line $nm$. Constraint (1e) is the power limits of transmission lines. Finally, (1f) indicates the voltage angle constraint.

B. Supplier Nodal Agents

The objective function of a supplier nodal agent $i \in \mathbb{I}$ is given in (2a), which consists of electricity generation cost in the first term, the revenue from the sold electricity in the second to sixth terms, and the penalties related to the coupling variable in the seventh term.
\[
\begin{align*}
&\min_{\theta_i, P_i, \theta, \lambda_i, \lambda, \lambda_{gb}} \\
&\quad \left(c_i(P_{i,g}) - \lambda_{i,g}P_{i,g} - \lambda_i^e(P_i)^T - \lambda_{i,bb}P_{i,bb}\right) \\
&\quad - \lambda_{i,gb} P_{i,gb} - \lambda_i \theta_i + \frac{\rho}{2} \left\| P_i - \hat{P}_i \right\|^2 + \left\| \bar{P}_{i,bb} - \hat{P}_{i,bb} \right\|^2 \\
&\quad + \left\| P_{i,g} - \hat{P}_{i,g} \right\|^2 + \left\| P_{i,gb} - \hat{P}_{i,gb} \right\|^2 + \left\| \theta - \hat{\theta}_i \right\|^2 \\
&\quad \text{s.t. } P_{i,g} - P_{i,g,1} = 0 \\
&\quad \quad P_i = (\theta - \hat{\theta}) X_i \\
&\quad \quad P_i^{\min} \leq P_i \leq P_i^{\max}, \quad P_{i,bb}^{\min} \leq P_{i,bb} \leq P_{i,bb}^{\max}, \\
&\quad \quad \theta_i^{\min} \leq \theta_i \leq \theta_i^{\max},
\end{align*}
\] (2a)

Constraint (2d) denotes the output constraint for the electricity supplier node connected with other nodes. Constraint (2e) indicates the range of voltage angle for the node $i$.

### C. Consumer Nodal Agents

The objective function of a consumer nodal agent $j \in \mathcal{G} = \{1, \ldots, J\}$ is given in (3a).

\[
\begin{align*}
&\min_{\bar{P}_i, \bar{P}_j, \theta, \lambda_i, \lambda, \lambda_{gb}} \\
&\quad -v_i(P_{i,d}) + \lambda_{i,d}P_{i,d} + (\lambda_i^e P_i)^T + \lambda_{i,bb}P_{i,bb} \\
&\quad + \lambda_{i,gb} \theta_i + \frac{\rho}{2} \left\| P_i - \hat{P}_i \right\|^2 + \left\| P_{i,bb} - \hat{P}_{i,bb} \right\|^2 \\
&\quad + \left\| P_{i,gb} - \hat{P}_{i,gb} \right\|^2 + \left\| \theta_i - \hat{\theta}_i \right\|^2 \\
&\quad \text{s.t. } P_{i,d} - P_{i,d}^b = 0 \\
&\quad \quad (\theta - \hat{\theta}) X_j \\
&\quad \quad P_{i,d}^{\min} \leq P_{i,d} \leq P_{i,d}^{\max}, \quad P_{i,bb}^{\min} \leq P_{i,bb} \leq P_{i,bb}^{\max}, \\
&\quad \quad \theta_i^{\min} \leq \theta_i \leq \theta_i^{\max},
\end{align*}
\] (3a)

where $P_{i,d}$ is the electricity demand of node $j$; $P_{i,d} = [P_{i,d}^b, P_{i,d}^f]$ is the electricity trading with node $j$ from other nodes; $P_{i,bb} = [P_{i,bb}^b, P_{i,bb}^f]$ is the node $j$'s trading electricity with EH; $\bar{\alpha}_j = \left[\bar{\alpha}_j^e, \bar{\alpha}_j^f\right]$ is the node $j$'s trading electricity with the upstream grid; $\lambda_{i,j}, \lambda_{i,bb}, \lambda_{i,gb}$, and $\lambda_{i,d}$ are the bid prices of the coupling variables $P_{i,j}, P_{i,bb}, \bar{\alpha}_j P_{i,d}$, and $\theta_j$; variables $\bar{P}_{i,d}, \bar{P}_{i,bb}, \bar{\theta}_j, \bar{\theta}_i$, and $\bar{P}_{i,gb}$ are the predetermined fixed values by RSO and EH.

Here, (3b) is the consumer nodes power balance. Constraint (3c) is the active power flow through transmission line connected with other nodes. Constraint (3d) denotes the constraint of electricity demand and the quantity traded with EH. Finally, (3e) indicates the range of voltage angle for the node $j$.

### D. Energy Hub

EH is an independent agent from the RSO that aims to make a profit by participating in market transactions by solving the problem (4).

\[
\begin{align*}
&\max_{\lambda_{gb}, \lambda, \lambda_{gb}} \\
&\quad \left(\lambda_{gb}^e \hat{P}_{gb}^e - \lambda_{gb}^o \hat{P}_{gb}^o - \lambda_{gb}^p \hat{P}_{gb}^p\right) \\
&\quad - \frac{\rho}{2} \left\| P_{gb}^e - \hat{P}_{gb}^e \right\|^2 + \left\| P_{gb}^o - \hat{P}_{gb}^o \right\|^2 \\
&\quad \text{s.t. } P_{gb}^e + P_{gb}^o + P_{gb}^p - P_{gb,i} = P_{gb,i}^{\text{max}}, \\
&\quad E_{i+1} = E_i + \frac{\eta_{gb}^p}{\eta_{gb}^e} P_{gb}^e - \frac{\eta_{gb}^o}{\eta_{gb}^e} P_{gb}^o \\
&\quad \frac{P_{gb,b}^{\min}}{\eta_{gb}^b} \leq \frac{P_{gb,b}}{\eta_{gb}^b, \max}, \quad P_{gb,b}^{\min} \leq \frac{P_{gb,b}}{\eta_{gb}^b, \max},
\end{align*}
\] (4a)

where the first two terms are trading revenue from the transaction with the regional transmission system, the third term represents the cost of purchasing natural gas, and the last term is the penalty. Constraint (4b) represents the electricity balance inside the EH. Constraint (4c) is the battery constraint. Finally, the range of EH trading volume is given in (4d).

### IV. DISTRIBUTED SOLUTION ALGORITHMS

In the previous section, a flow-based trading mechanism model for the regional transmission system and EH trading was devised to maximize the profits of all stakeholders. All market players, i.e., EH, supplier nodal agents, and consumer nodal agents within the regional transmission system, as rational stakeholders, aim to maximize their own profits by disclosing as little private information as possible in the market transactions. The formulated flow-based mechanism can be decomposed into the following: RSO behavior, EH behavior, and nodal agents’ behavior. Thus, the ADMM algorithm [7] pertains to implementing the DC power flow and clearance of the market as shown in Fig. 2.

![Figure 2. ADMM-based distributed method.](image-url)

The implementation process of the ADMM-based distributed method is as follows: First, the EH solves the optimization problem (4) based on initial electricity $P_{gb}^0 = [P_{gb,b}^0, P_{gb}^0]$ to determine the price $\lambda_{gb}^0 = [\lambda_{gb,b}, \lambda_{gb}^e, \lambda_{gb}^o]$. All nodes in the regional transmission system simultaneously develop bidding strategies. The consumer nodal agents' strategies are $P_c = [P_{c,gb}, P_{c,d}, \alpha_c, \theta_c]$ to maximize the value of electricity demand, and supplier nodal agents pursue minimize cost with strategies $P_s = [P_{s,gb}, P_{s,bb}, \alpha_s, \theta_s]$.

However, the power flow is coupled in each node and cannot be solved independently. Thus, the RSO updates the coupling variables by solving (5) based on the public nodal information.
A. Reformulated as:

The objective of EH in (4a) can be applied to solve the EH and transmission system market clearing problems, the algorithm will be terminated. The following assumptions and linearization method are used to find the optimal solution.

A. Decomposed DC Power Flow

Assumption 1: The cost function $c_i; R^i \cup \{+\infty\}$ and value function $v_j; R^j \cup \{+\infty\}$ are closed, proper, and convex.

Assumption 2: The overall optimization problem has strictly feasible solutions, and the overall optimization problem consists of convex inequality constraints and affine equality constraints.

Assumptions 1 and 2 satisfy Slater’s strong duality condition, so the proposed algorithm has the convergence and global optimality conditions [7]. As a result, the iterative results of decomposed DC power flow satisfy the residual, objective, and dual variable convergence.

B. Binary Expansion Linearisation Method

The product terms $\lambda_{b,b}^{h}, \lambda_{b,g}^{f},\hat{b}_{h,b}$ in the EH objective function (4a) are nonlinear and non-convex. For these bilinear product terms $\lambda_{b,b}^{h},\hat{b}_{h,b}$, where $\lambda_{b,b}^{h}$ and $\hat{b}_{h,b}$ are continuous variables, a binary expansion method [9] is applied to linearize them. Thus, the binary expansion linearization method is applied to solve the EH and transmission system market clearing problems. The objective of EH in (4a) can be reformulated as:

$$\min_{\lambda_{b,b}^{h},\hat{b}_{h,b}} \sum_{\lambda_{b,b}^{h},\hat{b}_{h,b}} \left( \lambda_{b,b}^{h} \hat{b}_{h,b} + \lambda_{b,b}^{h} \hat{b}_{h,b} \cdot \left( P_{b} - P_{b}^d \right)^{2} - \lambda_{b,b}^{h} \hat{b}_{h,b} \cdot \left( P_{b} - P_{b}^d \right)^{2} \right)$$

s.t. $0 \leq P_{b} - P_{b}^d \leq P_{b}^{\text{max}}, \forall \tau$

Here, the objective (7a) provides a linear expression of $\lambda_{b,b}^{h},\hat{b}_{h,b}$ and $\lambda_{b,b}^{f},\hat{b}_{h,b}$. The approximation accuracy of binary expansion can be controlled by the number of expansion segments. The flow-based distributed trading mechanism in the REM with EH is a mixed-integer linear programming (MILP) problem, which can be solved by commercial solvers directly.

V. CASE STUDIES

A. System Parameters

To verify the effectiveness of the mechanism, we adopted a case study of a regional transmission system with an EH in Jiangsu Province, in southeastern China. This regional transmission system is connected to the upstream grid at node 1 and node 5, and a gas turbine produces electricity at node 4. The EH with CHP and battery storage connects to the regional transmission system at node 2, as shown in Fig. 3. Detailed system data can be found in [10]. The price of natural gas is assumed to be 265$/MWh and the price of selling electricity to the upstream grid is 90$/MWh.

B. Analysis of Regional Electricity Market Clearing

The regional system participates in the wholesale market by interacting with the upstream grid while trading with EH. Fig. 4 shows the energy trading results, and Fig. 5 shows the price in the market.

In the day-ahead, nodal agents in the regional transmission system buy electricity from the upstream grid via node 1 while reselling electricity to the upstream grid via node 5 to achieve the cross-arbitrage, due to the difference between the purchase...
and the sale. During periods 7-8, the price of electricity sold by EH is in the valley periods and is almost equal to the price of electricity sold from the upstream grid. Hence, the transmission system buys part of the electricity from EH and resells it to the upstream grid through node 5. In addition, the prices of electricity sold by EH and by the upstream grid are very close in periods 19 to 22. While prices are not the lowest at this point, the regional transmission system can still cross-arbitrage in transactions between EH and the upstream grid.

![Figure 6](image6.png)

**Figure 6.** The amounts of purchased natural gas and state of charge of the battery storage in the EH.

The amounts of purchased natural gas by EH are shown in the first subplot of Fig. 6 and the state of charge of the battery storage inside the EH is indicated in the second subplot of Fig. 6. The EH purchases natural gas before discharging to benefit from selling electricity to the regional transmission system. It is interesting to note that during periods 10-15, EH only buys electricity from the regional transmission system instead of purchasing natural gas and converting it into electricity. It is because the cost of electricity purchased by EH from the regional transmission system during this period is much lower than the cost of purchasing natural gas for natural gas-to-electric conversion.

![Figure 7](image7.png)

**Figure 7.** Price and electricity of transactions between different nodes.

It can be observed from the first subplot of Fig. 7 that nodes C1 and C2 have the most variation in the price, while C2 has the option to purchase power from C1 and EH, both of which fluctuate at around 60$/MWh. In addition, the price of C1-C2 varies proportionally with the quantity of transactions. The prices of C1-C3, C1-S4 and C3-S4 are almost the highest, because C1 purchases power from the upstream grid and resells it to C3 and S4 to increase the revenue. It is interesting to note that these three prices are very close to each other. C3 as a consumer node can only obtain power from S4 and C1, whereas every nodal agent wants to benefit from the market that leads to this price phenomenon. Nodes C2-C5 have the lowest prices, and C2 can sell electricity to the EH and nodal agent C5, simultaneously. Comparing the EH purchase price in Fig. 5 with the purchase price for C5 in the first subplot of Fig. 7, the two prices are comparable in the periods of 0 to 5 and 9 to 18. However, the purchase prices of EH increased dramatically during the periods from 18 to 23, whereas the prices of C2-C5 have also steadily risen. During this period, C2 only sells electricity to the C5, not the EH. Next, the results of the proposed distributed mechanism are compared with those of the centralized method. Table I shows the comparison of agents’ value (v), cost (c), revenue, and social welfare (SC) in the centralized and distributed methods. EH and regional transmission systems have more benefits in the distributed clearing approach than in the centralized clearing method. This is because, under the distributed algorithm, nodes C1 and C5 act as rational agents and increase their revenue by trading with the upstream grid and reselling to the other nodes.

| Model    | Player | v (v) | c ($/MWh) | Revenue ($) | SC ($) |
|----------|--------|-------|-----------|-------------|--------|
| Distributed | C1     | 408.09| 1344.15   | 994.96      | 363.06 |
|          | C2     | 650.67| 431.63    |             |        |
|          | C3     | 373.54| 376.23    |             |        |
|          | S4     | 1123.87| -837.67  |             |        |
|          | C5     | 468.94| 433.07    |             |        |
| Centralized | EH    | 414.11| 12.5      | 352.26      | 163.71 |
|          | C1     | 213.42| 19.47     |             |        |
|          | C2     | 703.26| 702.94    |             |        |
|          | C3     | 111.05| 111.05    |             |        |
|          | S4     | 1201.77| -1201.77 |             |        |
|          | C5     | 468.95| 720.57    |             |        |
|          | EH     | 131.2 | 3.2       |             |        |

VI. CONCLUSION

This paper proposes a flow-based hierarchical trading mechanism that integrates an EH into the operation of the REM. The EH acts as an independent agent in the regional transmission system, purchasing fuel from the natural gas market and trading with the nodal agents. Different nodal agents intend to cross-arbitrage with the EH and upstream grid. A REM clearing is proposed to be realized via an ADMM-based distributed algorithm. The DC power flow is calculated by the RSO and nodal agents in a distributed manner while considering the privacy concerns. The case study shows that the flow-based trading mechanism provides a good incentive for EH and distributed energy sources to participate in the market to improve energy efficiency. Furthermore, the effectiveness and convergence of the algorithm are also well proved.

Future research will consider power to natural gas equipment in the model of EH and the use of hydrogen as an object of transaction for joint clearing of multi-energy markets. Privacy will be a primary consideration for agents in future studies.

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