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Peer-to-peer energy sharing with dynamic network structures

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HIGHLIGHTS

- A joint framework with P2P energy sharing and dynamic network structure is proposed.
- A dynamic network structure model affected by the P2P energy sharing is provided.
- A solution algorithm with matching processes and branch-exchange is designed.
- The effectiveness of the proposed framework is demonstrated.

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ABSTRACT

The integration of distributed energy resources facilitates peer-to-peer (P2P) energy sharing as an effective way to coordinate the energy scheduling. Previous research has focused on economic P2P energy sharing of user side without considering the possible response strategies of network sides. This paper proposes a P2P energy sharing framework that takes into consideration the dynamic network structure. A P2P energy sharing model aimed at increasing the energy local consumption and reducing each prosumers' power losses arisen from P2P energy sharing is built for the P2P energy schedule. In the physical network, a dynamic network structure model is designed to incorporate the network operator into the energy sharing process, and obtain the better network structure while reducing the power losses of whole network. These two proposed models are jointly optimized by the upper and lower layer to get the optimal P2P energy sharing schedule, network operations conditions and comprehensive energy utilization. The solution algorithm for the joint optimization is composed of a designed matching mechanism and branch-exchange method and realized by the iteration process. Finally, numerical analysis reveals the effectiveness of the proposed framework in terms of prosumers' strategies, network structures, comprehensive energy utilization, and practical feasibility.

1. Introduction

Distributed energy resources (DERs) are gradually integrated into the user side, thus rendering users as prosumers with the ability of production and consumption [1]. Prosumers who access the distribution network play active participants in managing their generation and consumption. The active role of prosumers and random characteristics of DERs brings negative influence in the smart grid, e.g., reduce the power quality, complex the power flow, and lead to difficulties for energy schedule. As the use of DERs expands and the increasing number of prosumers, a paradigm shift of smart grid schedule has been triggered from centralized design to distributed design [2]. Peer-to-peer (P2P) energy sharing is one of the promising energy management methods that can efficiently coordinate prosumer's energy sharing with other prosumers in a distributed way [3].

The P2P energy sharing enables the energy balanced to the greatest extent in the sharing area, reduces the electricity cost of prosumers, decreases the power losses, and improves the energy efficiency [4]. As the concept that the smart grid exhibits characteristics typical of cyber-physical system (CPS) in energy [5], the P2P energy sharing is also studied from the perspective of CPS. The technical approach for realizing the P2P energy sharing schedule can be mainly divided into three categories: (i) Game theory approach, (ii) Blockchain technology approach, and (iii) Other optimization approach. The game theory can reflect the complex and diverse relationship of prosumers in P2P energy sharing [6,7]. The Stackelberg game is a major game model that can describe the interactions between sellers and buyers, set sellers as leaders and buyers as followers [8]. The game is also used to formulate the third parties as the leader to coordinate the energy sharing among

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Nomenclature

Parameter

- h, H Index and total number of time slot.
- i Index of prosumers (node), which includes sellers i_s and buyers i_b.
- N Total number of prosumers, which includes sellers set N_s, and buyers set N_b.
- t, T Index of iteration, and maximum number of iterations in P2P energy matching.
- m, M Index, and total number of loops in the network.
- $\beta_{i,h}$ Parameter of the prosumer i in terms of trading energy with the utility grid.
- γ_{i_s,i_b} Loss sensitivity factors between the node that sellers i_s and buyers i_b access to.
- μ Parameter of the P2P matching.
- $fL_{i,h}$ Fix load of prosumer i in time slot h.
- $E_{i,h}$ PV generation of prosumer i in time slot h.
- $L_{\mathrm{P2P,min}}, L_{\mathrm{P2P},max}$ The lower and upper limit of P2P trading energy.
- $Q_{k,h}$ Reactive power of branch k at time slot h.
- s_m, S_m Number of switches in loop m, and the set of s_m.
- R_k Resistance of the branch k.
- $U_{i,h}$ Voltage of the node that prosumer i access in time slot h.
- $P_{k,h,0}$, $U_{i,h,0}$ Initial active power of brank k and node voltage that prosumer i access in time slot h.
- ε The error-tolerant rate.
- ξ Comprehensive energy utilization.
- $\frac{\partial V}{\partial P}$ Voltage sensitivity coefficients vector.
- $G_{k-i_s i_b}$ Power transfer distribution factors between sellers i_s and buyers i_b.

Variable

- $sL_{i,h}$ Flexible load of prosumer i in time slot h.
- $L_{i,h}$, $nL_{i,h}$ Total load consumption and netload of prosumer i in time slot h.
- $D(i_s,i_b)$ P2P trading matching-pair of seller i_s and buyer i_b.
- $\boldsymbol{L}_{\mathrm{P2P},h}$, $L_{\mathrm{P2P},i_s,i_b,h}$ P2P trading matrix in time slot h, whose elements indicates trading energy between seller i_s and buyer i_b.
- $L_{\mathrm{s},i_s,i_b,h}$,$L_{\mathrm{b},i_b,i_s,h}$ Selling energy from the seller i_s to the buyer i_b and the buying energy of the buyer i_b from the seller i_s.
- $L_{\mathrm{b},i_b,h}$, $L_{\mathrm{s},i_s,h}$ Total buying energy of buyeri_b and total selling energy of seller i_s.
- $\boldsymbol{A}_k$ Node-to-branch incidence vector of the branch k.
- $\eta_{k,h}$, $\boldsymbol{\Phi}_h$ The switch's state in the branch k in time slot h, and the set of $\eta_{k,h}$.
- $\boldsymbol{\eta}_{i_s,i_b,h}$ The switch's state in the electrical pathway between seller i_s and buyer i_b, which includes multiple branches.
- $aE_{i,h}$ Energy local consumption of prosumer i in time slot h.

P2P prosumers, which serve as followers and achieving the equilibrium between the manager and prosumers [9,10]. The social attributes of prosumers are also included in the Stackelberg game with stochastic modeling [11], and the stochastic modeling can also be used to formulate the uncertainties from PV energy, electricity prices, and prosumer's load [12]. It is noted that the Stackelberg game mainly builds the P2P relationship in a competitive way, the cooperative Stackelberg game is also existed, which is applied to help a centralized system to reduce the total electricity demand at the peak hour [13]. In addition to the Stackelberg game, The P2P energy sharing framework is also modeled by multiple game models. The contract game model is built to coordinate different types of electricity markets with large-scale and small-scale energy resources [14]. To deal with the risk from uncertain energy resources and demand, a two-stage stochastic game model is proposed with Cournot Nash pricing mechanism and the conditional value-risk criterion [15]. The non-cooperative game is provided to realize the economic and sustainable P2P energy sharing among energy building, keeping the fairness [16], and facilitate a regional building cluster with the distributed transaction technology [17]. Besides, the cooperative game can be used to design a motivational psychology P2P trading framework [18] while building suitable social coalition groups with similar prosumers [19].

Blockchain technology (BT) is another widely used technical approach for realizing P2P energy sharing to ensure the security and transparency of the sharing process [20]. In the blockchain, the smart contract is a mainly kind of computerized transaction protocol, which is scripts stored on the blockchain with a unique address while support BT to balance regional energy and mitigate carbon emission in P2P energy sharing framework [21]. The consortium BT with the advantages of moderate cost, better scalability, and shorter delay is efficient in energy scheduling to improve energy quality and build a secure energy trading system [22,23]. The consortium BT based trading model is also proposed to activate the prosumers to compensate the power losses and increase the income of P2P traders [20]. Many software platforms based on BT are developed for the P2P energy sharing, like Hyperledger for cross-industry application [24], and Elecbay for P2P trading within a microgrid [25]. Besides, BT is also utilized with other trading mechanisms to handle diverse trading preferences arisen from the prosumers' social attributes [26], and combined with fuzzy multi-objective programming to tackle the variability of load demand and renewable generation [27]. Other optimization methods are also used in P2P energy sharing. To implement the residential user's demand response in a P2P method, a bilevel optimization model with pricing scheme is used to optimize economic cost and user' willingness while encouraging the local trading of photovoltaic energy [28]. For privacy security and sustainable energy society, the alternating direction method of multipliers (ADMM) is used to modeling a two-phase energy sharing framework [29], and distributed interior point method via θ-logarithmic barrier is provided to avoid centralized communication that violates privacy requirements in the dynamical multiagent system [30]. Besides, the mixed-integer linear programming model is proposed for the increasement of economic benefits in the photovoltaic (PV)-battery based P2P trading systems [31]. This research mainly aims at realizing the maximum economic benefits for prosumers and other stakeholders by the scheduled method of the cyber field. However, the energy sharing process conducted in the actual network is limited by the network operation conditions and has a negative influence on them.

In the physical network, the P2P energy sharing will complex the power flow, results in the violation of voltage and capacity constraints, increase power losses of the network, and weaken the system strength [32,33]. To solve these problems, some research takes network operation conditions into consideration. A P2P market was designed to handle the violations of grid constraints through the ancillary service market, which statically considers the operation conditions in the constraints [34]. However, the P2P energy sharing process is not constant, and the network operation conditions are also dynamically changed. To consider the dynamic network influence, a network management system based on a multi-agent and multi-layer control mechanism is proposed, where the network power losses are considered as an optimization function [35], Similarly, a sensitivity analysis method for assessing the impact of P2P transactions on the network while guarantee the energy exchange within the network constraints [36]. However, existing research only

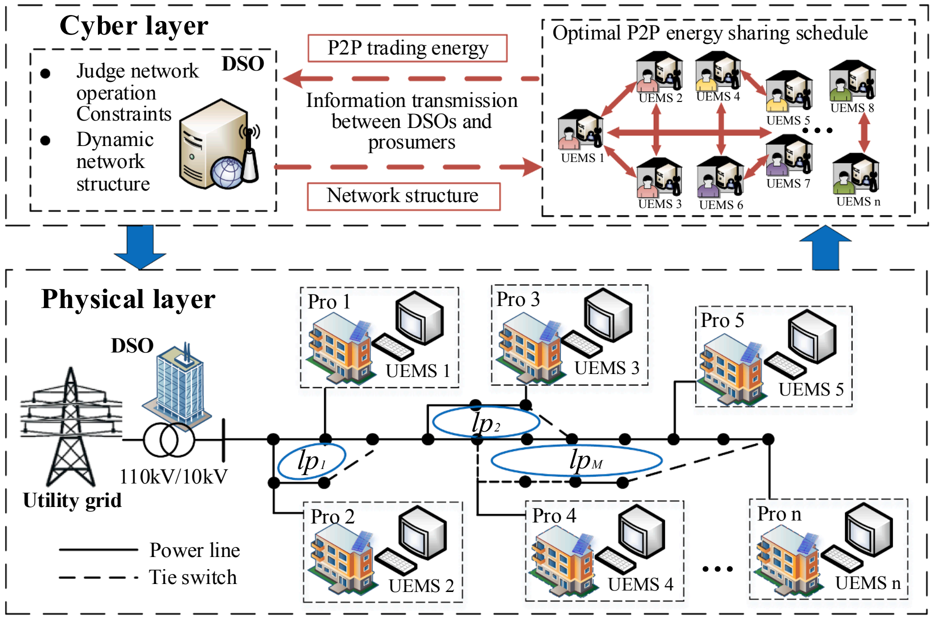

Fig. 1. Framework of P2P energy sharing.

consider the influence of network operation conditions on the P2P energy sharing process in a passive way, rather than the dynamic network structure which could change the network operation conditions during the P2P energy sharing.

To optimize the energy utilization, the dynamic network structure in the P2P energy sharing process can get better network conditions that fit the optimal P2P energy sharing schedule and network operation, which also complicates the energy scheduling and deserves extensive exploration [37]. This complexity presents three challenges: (i) The maximal energy usage P2P energy sharing framework that can realize the matching of P2P traders while dynamically consider the network operation conditions; (ii) How to consider the dynamic network structure into the P2P energy sharing and reach an equilibrium for both network operation and prosumers energy sharing; and (iii) The solution algorithm for the joint optimization of these two processes with the coupled strategies of prosumers and network operators.

To address the aforementioned challenges, a P2P energy sharing framework considering dynamic network structures is proposed. This is a new framework to enable the network side to have strategies to respond to the energy scheduling in the user side, incorporate the network into the energy scheduling and connect the energy scheduling and dynamic network structure, which has not been reported, as far as we know. The contributions of this paper are as follows:

(1) A P2P energy sharing model is proposed for optimizing the energy scheduling. The proposed model considers the minimum power losses of each prosumer and energy local consumption as the goal. To formulate this model, a matching model is built for each prosumer with coupled load strategies and P2P trading strategies.
(2) The dynamic network structure model is designed under the coupling influence of the P2P energy sharing process, which aims at reducing power losses of whole network while increasing the P2P energy sharing. Combining with the P2P energy sharing model, a joint optimization model is built to increase comprehensive energy utilization while realizing the optimal operation conditions for P2P energy sharing and network operations.
(3) The solution algorithm for jointly optimizing the coupled process of network structure and P2P energy sharing schedule is proposed. In the algorithm, a process for realizing P2P matching is designed based on the trading matrix which is updated by the iteration between P2P traders, and the branch exchanged method is introduced for obtaining the optimal network structure.

2. P2P energy sharing framework and model

2.1. Framework

The framework of this P2P energy sharing system is fully distributed, which is shown in Fig. 1. From the perspective of CPS, in the cyber layer, the energy sharing schedule of each prosumer is optimized to reach minimal energy cost, power losses, and maximum trading utility. In the physical layer, the network is described as many loops ($lp_m, m \in M$), which is composed of many switches [38]. One prosumer access to one node in the physical electricity network, and the energy is actual traded in the network according to the scheduling under the consideration of network operation constraints. The P2P energy sharing framework realizes the joint consideration of the energy scheduling and network operation.

The framework is composed of distributed system operators (DSOs) and prosumers with a user energy management system (UEMS). Prosumers are equipped with PV panels and can trade energy between each other based on the role of sellers and buyers, which is determined by their PV generation and load demand. The buying energy of a buyer requires to match with the selling energy of a seller if the seller and buyer want to conduct P2P energy trading. The optimal energy schedule and P2P matching are proceeding in the cyber layer. During actual energy trading in the physical layer, the energy will generate power losses in the network, which includes two parts, (i) generated by P2P sharing energy and (ii) generated by trading energy with the utility grid. Prosumers will take the first part when conduct the P2P energy sharing.

The DSO in the framework is in charge of the network operation, control the network structure, and take the second part power losses in the physical layer. The electricity energy exchange is different from any other exchange of goods, and the prosumers are part of the network [37]. Electricity characteristics, such as balance and instantaneity, are reflected by some technical network constraints. The constraints, including voltage stability, power line transmission limit, generation and demand balance, capacity constraints, etc., should be satisfied during the actual energy sharing of prosumers. Meanwhile, the network operation conditions are also affected by the energy sharing schedule. To consider the interactive influence between the physical network and energy scheduling, the DSO can change the state of switches (i.e., open or closed) to dynamically optimize the network structure aimed at minimizing power losses and promoting P2P energy sharing. The communication between these two entities during the P2P energy sharing process is based on wireless channels [39].

2.2. P2P energy sharing model of prosumers

The prosumers' load strategies and P2P energy sharing strategies are optimal scheduled by the energy sharing model before its actual conduct in the physical network.

2.2.1. Load model

Prosumers that participate in the P2P energy sharing are grouped into sellers and buyers, which have PV generation and load consumption. The PV generation is recorded by the PV equipment of each prosumer, and the load model is expressed as:

$$L_{i,h} = sL_{i,h} + fL_{i,h}, i \in N, h \in H \tag{1}$$

$$nL_{i,h} = L_{i,h} - E_{i,h} \tag{2}$$

where $nL_{i,h}$ determine the role of the seller when $nL_{i_s,h} < 0, i_s \in N_s$, and the role of the buyer when $nL_{i_b,h} > 0, i_b \in N_b$.

The day-ahead energy scheduling is adopted in the research. During the whole-time scale, the flexible load can be adjusted in different hours within a specific limit. The constraints of flexible load can be expressed as:

$$sL_{i,h,min} \le sL_{i,h} \le sL_{i,h,max}, i \in N, h \in H \tag{3}$$

$$\sum\nolimits_{h=1}^{H} sL_{i,h} = tL_i, i \in N \tag{4}$$

where the $sL_{i,h,min}$ and $sL_{i,h,max}$ is the lower and upper limit of flexible load adjustment, tL_i is the total load of the entire time scale, and the flexible load adjustment in one day should satisfy the sum constraint.

2.2.2. Matching model

Based on the role of each prosumer in the P2P energy sharing, the sellers can send energy to the buyers if they have a similar energy surplus and load demand while reaching a matching. In the matching model, the buyer j can form a matching-pair $D(i_s,i_b)$ with the seller i_s, which is expressed as:

$$D(i_s, i_b) = (L_{\mathrm{P2P},i_s,i_b,h} | L_{\mathrm{s},i_s,i_b,h} = L_{\mathrm{b},i_b,i_s,h}, i_s \in N_s, i_b \in N_b) \tag{5}$$

The P2P trading energy $L_{\mathrm{P2P},i_s,i_b,h}$ is determined by the selling energy of the seller i_s and buying energy of the buyer i_b.When $L_{\mathrm{s},i_s,i_b,h} = L_{\mathrm{b},i_b,i_s,h}$, the P2P energy sharing can be conducted between the seller i_s and the buyer i_b, then the P2P trading energy $L_{\mathrm{P2P},i_s,i_b,h}$ is obtained by:

$$L_{\mathrm{P2P},i_s,i_b,h} = L_{\mathrm{s},i_s,i_b,h} \mathrm{or} L_{\mathrm{P2P},i_s,i_b,h} = L_{\mathrm{b},i_b,i_s,h} \tag{6}$$

One seller can set multiple $L_{\mathrm{s},i_s,i_b,h}$ to different buyers and form multiple matching-pairs, which is the same for the buyer. For the sellers and buyers, the P2P trading energy in one time slot is limited by their netloads, which determines the energy that can be shared. Then the following constraints should be satisfied:

$$\sum\nolimits_{i_b=1}^{N_b} L_{\mathrm{P2P},i_s,i_b,h} \le |nL_{i_s,h}|, i_s \in N_s, h \in H \tag{7}$$

$$\sum\nolimits_{i_s=1}^{N_s} L_{\mathrm{P2P},i_s,i_b,h} \le nL_{i_b,h}, i_b \in N_b, h \in H \tag{8}$$

The key to the matching model is to find the possible matching-pairs through selling and buying energy, the matching is realized by the optimization of P2P energy sharing.

2.2.3. P2P energy sharing model

To reduce the impact of flexible DERs on the system operation, the network power losses, and take the physical network operations into considerations. For each seller and buyer, the P2P energy sharing model is formulated as follows:

$$f_{i_s} = \sum\nolimits_{h=1}^{H} \sum_{i_b=1}^{N_b} (\beta_{i_s,h} \cdot (nL_{i_s,h} - L_{\mathrm{P2P},i_s,i_b,h}) + \gamma_{i_s,i_b} \cdot L_{\mathrm{P2P},i_s,i_b,h} + |\mu \cdot L_{s,i_s,h} - L_{b,i_b,h}|), i_s \in N_s \tag{9}$$

$$f_{i_b} = \sum\nolimits_{h=1}^{H} \sum_{i_s=1}^{N_s} (\beta_{i_b,h} \cdot (nL_{i_b,h} - L_{\mathrm{P2P},i_s,i_b,h}) + \gamma_{i_s,i_b} \cdot L_{\mathrm{P2P},i_s,i_b,h} + |\mu \cdot L_{s,i_s,h} - L_{b,i_b,h}|), i_b \in N_b \tag{10}$$

where f is a potential cost described by the energy, $\sum_{h=1}^{H}(\cdot)$ indicates that the energy sharing is conducted day-ahead, $\sum_{i_b=1}^{N_b}(\cdot)$ and $\sum_{i_s=1}^{N_s}(\cdot)$ is respectively all the buyers and sellers that trade with seller i_s and buyer i_b.

The goal of this model is to realize the following effect by P2P energy sharing: (i) Reduce the amount of energy that prosumers trade with the utility grid, including the selling energy of seller and buying energy of buyer, to enhance the local consumption of DERs. (ii) Reduce power losses for each prosumer during the actual P2P energy sharing.

The first term of the model $\beta_{i_s,h} \cdot (nL_{i_s,h} - L_{\mathrm{P2P},i_s,i_b,h})$ is the energy that should be traded with utility gird, which may cause negative influence and means a potential risk on the system. If without the P2P energy sharing, all netload of both sellers and buyers is required to trade with the utility grid.$\beta_{i_s,h}$ is a parameter that judges the influence of energy trading with the utility grid on the system and balances the effect of power losses and trading energy. The larger $\beta_{i_s,h}$ means large influence on the system operation and the bigger gap between trading energy and power losses.

The second term are power losses of P2P energy sharing. Because the prosumers are both the sources and load for P2P trading energy, the power losses arisen from P2P trading energy should be covered by the prosumers, which can also be regarded as a cost for prosumers. Therefore, these losses are considered during the prosumers conducting P2P energy sharing schedule.

The third term is the unmatched selling energy of sellers and buying energy of buyers, which will lead to cost if the P2P trading cannot match. The sellers and buyers set the amount of energy they want to trade at the beginning. In general, they cannot reach an agreement at the first time, while after serval iterations between each possible trading prosumers, their trading energy should get close, or they will give up each other and find new trading partners. To facilitate their matching, the unmatched energy is minimized in this model, and μ is set to control the matching rate. Higher μ indicates fast matching but may ignore the prosumers willingness and increase power losses in other terms. However, because the selling energy and buying energy may not always balanced and the selling and buying willing of each prosumer may not matching, there may exist single seller or buyer with unbalance energy. The single seller or buyer will trade their unbalanced energy with the utility grid.

In the energy sharing model, the variables are the flexible load and P2P trading energy of each prosumer, which is also coupled through the netload in each time slot. Constraints are also related to these two variables:

$$0 \le L_{\mathrm{P2P},i_s,i_b,h} \le L_{\mathrm{P2P,max}} \tag{11}$$

$$L_{\mathrm{P2P,min}} \le L_{\mathrm{P2P},i_s,i_b,h} \le 0, i_s \in N_s, h \in H \tag{12}$$

$$\sum_{i_s \in N_s} L_{\mathrm{P2P},i_s,i_b,h} = L_{b,i_b,h}, i_b \in N_b, h \in H \tag{13}$$

$$\sum_{i_b \in N_b} L_{\mathrm{P2P},i_s,i_b,h} = L_{s,i_s,h}, i_s \in N_s, h \in H \tag{14}$$

where $L_{\mathrm{P2P,max}}$ and $L_{\mathrm{P2P,min}}$ are the upper and lower limit of P2P trading energy, respectively; $L_{b,i_b,h} = \sum_{i_s \in N_s} L_{b,i_b,i_s,h}$, and $L_{s,i_s,h} = \sum_{i_b \in N_b} L_{s,i_s,i_b,h}$

For flexible load, there are N number of flexible load sum constraints Eq. (4) and $N \cdot H$ number of flexible load value constraints Eq. (3). Besides, there are $N \cdot H$ number of value constraints for P2P trading energy Eq. (11). For each buyer, the amount of electricity buying from multiple sellers should equal to its total P2P trading energy, expressed as $N \cdot H$ number of constraints Eq. (13). To satisfy the energy balance for each prosumer, there are $N \cdot H$ number of inequality constraints to limit the P2P trading energy less than the netloads Eqs. (7) and (8). Therefore, $N(1 + 4H)$ constraints are included in the P2P energy sharing model.

3. Dynamic network structure during P2P energy sharing

3.1. Interactive influence between P2P energy sharing and network structure

The P2P energy sharing should conduct in the actual network with the optimal energy scheduling. In the physical network, the matching P2P trading energy of sellers and buyers will affect the network operation conditions by changing the netload of prosumers and trading energy. Besides, the P2P trading energy should also satisfy the network operation constraints controlled by the DSO. There are two kinds of influence in terms of the physical network and P2P energy sharing:

3.2. Dynamic network structure model

Distribution networks are composed of many loops and generally operate in the open-loop state. To describe the distribution network, and reduce the computation time of the electrical parameters, the impact of node power changes on network operation is estimated by the sensitivity analysis methods. The electrical parameters (i.e., node voltage, branch power flow, and network loss) will be affected by the P2P energy sharing, which are analyzed by the voltage sensitivity coefficients (VSCs), power transfer distribution factors (PTDFs), and loss sensitivity factors (LSFs) described in Re. [36]:

The network structure can be dynamically adjusted by changing the state of switches, and the branch power flow will also be correspondingly changed. The goal of network structure adjustment is to realize the better operation condition, i.e., minimizing power losses of whole network, improving the P2P energy sharing while keeping the operation constraints of node voltage, transmission line, and radial structure.

The connecting branch and power flow of the distribution network will be affected by the network structure, so will the power losses and electrical pathway of P2P energy sharing. Therefore, the network power losses and electrical pathway of P2P energy sharing can be optimized through dynamically changing the network structure. The dynamic network structure model for minimal power losses and promoting P2P energy sharing is formulated as a function of the switches' state, the flexible load strategy, and the P2P trading energy schedule. The constraints of the optimization problem are composed of the power line transmission limit, node voltage constraint, and radial structure of the distribution network [40], which can be expressed as follows:

$$min \Delta P_{\Sigma}\left(\boldsymbol{\Phi}, sL_{i,h}, \boldsymbol{L}_{P2P,h}\right) = \sum_{h=1}^{H} \sum_{i \in N} \sum_{k=1}^{N-1} \left(\eta_{k,h} R_k \frac{\left(\Gamma_k\left(nL_{i,h} - \left(L_{s,i,h}, L_{b,i,h}\right)^*\right) + \boldsymbol{\eta}_{i_s,i_b,h}^T\left(\boldsymbol{L}_{P2P,h}\boldsymbol{A}_k\right)\right)^2 + Q_{k,h}^2}{U_{k,h}^2} + \gamma_{i_s,i_b}\left(L_{s,i,h}, L_{b,i,h}\right)^*\right) \tag{15}$$

(1) ***For the physical network.*** The multi matching of P2P trading energy will change the electrical parameters of the physical network, such as variable node voltage and complex branch power flow presenting the character of bi-direction and flexibility. The network operation will be affected, e.g., some lines overload, other lines underload and larger power losses, which has negative influence on the network operation condition.
(2) ***For the P2P energy sharing***. The operation conditions of physical network will suboptimize the prosumers energy scheduling, promoting prosumers to revise their P2P trading energy and flexible load strategies to fit the network operation conditions, e.g., suppose the seller i_s and buyer i_b should trade $L_{\mathrm{P2P},i_s,i_b,h}$ energy, which will go through the power line $i_s - i_b$, if the trading energy larger than the power line transmission limit, the energy cannot be traded and a new energy schedule should be set that deviates from the previous optimal one.

It is obvious that the prosumers and DSO are affected by each other, their respective optimal strategies cannot be conducted when consider both two entities in real implementation. The P2P energy scheduling is unable to successfully conduct in an optimal schedule when the network conditions are not be considered, and the optimal network operation conditions are also deviated because of the P2P energy sharing. Therefore, the dynamic network structure is incorporated in the P2P energy sharing to convert the DSO to an active participant that can respond to the P2P energy sharing schedule, then obtain optimal solutions for both prosumers and DSO.

$$s.t.\ P_{min\_k,h} \le \Gamma_k\left(nL_{i,h} - \left(L_{s,i,h}, L_{b,i,h}\right)^*\right) + \boldsymbol{\eta}_{i_s,i_b,h}^T\left(\boldsymbol{L}_{P2P,h}\boldsymbol{A}_k\right) \le P_{max\_k,h} \tag{16}$$

$$U_{min} \le U_{k,h} \le U_{max} \tag{17}$$

$$\sum_{i_s \in N_s, i_b \in N_b} \sum_{k=1}^{N-1} \boldsymbol{A}_k^T \boldsymbol{\eta}_{i_s,i_b,h} = N - 1 \tag{18}$$

$$\omega_{ab} + \omega_{ba} = \boldsymbol{A}_k^T \boldsymbol{\eta}_{i_s,i_b,h} \tag{19}$$

$$\sum_{n \notin N_{Sub}} \omega_{ab} = 1 \tag{20}$$

$$\sum_{n \in N_{Sub}} \omega_{ab} = 0 \tag{21}$$

where $\Gamma_k(\cdot)$ is the power flow calculation function of the branch k; $(\cdot)^*$ is the projector of $nonzeros(0, \cdot)$, where for a prosumer, one of $L_{s,i,h}, L_{b,i,h}$ will be zero; $\eta_{k,h} = 0$ if the state of switch in branch k is open, otherwise $\eta_{k,h} = 1$; $P_{min\_k,h}$ and $P_{max\_k,h}$ are the lower and upper limit of the branch k's transmission capacity, U_{min} and U_{max} are the lower and upper bound of node voltage,ω_{ab} is a binary variable indicating if the node a is the parent node with respect to node b, if it is, $\omega_{ab} = 1$, otherwise, $\omega_{ab} = 0$, N_{Sub} is the set of substation nodes (i.e., power source nodes).

The power losses of each branch are determined by their switch's states, resistance, node voltage, active and reactive power. The active power of each branch is calculated by

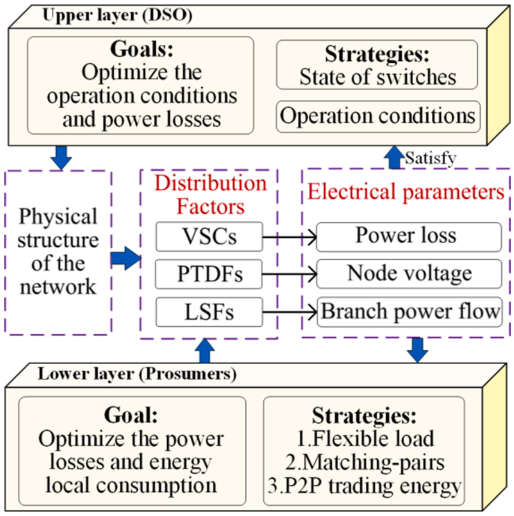

Fig. 2. The interactive influence of joint P2P energy sharing process.

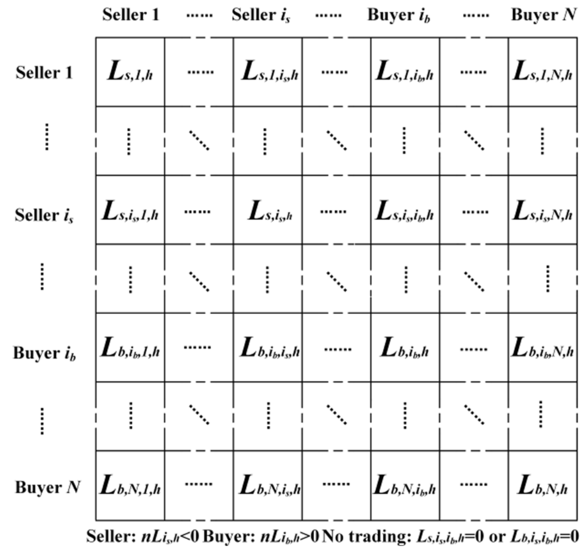

Fig. 3. The P2P trading matrix in time slot h.

$\Gamma_k(nL_{i,h} - L_{P2P,i_s,i_b,h}) + \boldsymbol{\eta}^T_{i_s,i_b,h}(\boldsymbol{L}_{P2P,h}\boldsymbol{A}_k)$, the first part of active power is calculated by the power flow function $\Gamma_k(\cdot)$ based on the trading energy with the utility grid, i.e., netload minus P2P trading energy. The second part is the P2P trading energy in branch k. $\boldsymbol{\eta}^T_{i_s,i_b,h}$ is a column vector contains multiple branches, $\boldsymbol{L}_{P2P,h}$ is a $N \times N$ matrix, and $\boldsymbol{A}_k$ is a column vector with N nodes, thus, $\boldsymbol{\eta}^T_{i_s,i_b,h}(\boldsymbol{L}_{P2P,h}\boldsymbol{A}_k)$ is a real number, which guarantees the additivity with the first part of active power. The $\gamma_{i_s,i_b}(L_{s,i,h}, L_{b,i,h})^*$ is also a part of the power losses that use to consider P2P energy sharing schedule into the network side, which enable dynamic network structure promote energy sharing.

Eqs. (16) and (17) are respectively the constraints of the power line transmission capacity and node voltage constraints, which restrict the transmission energy in each branch and node voltage within the operation requirement. Eqs. (18)–(21) are the radial structure constraint, i.e., Eq. (18) guarantees the network structure to be a tree, Eq. (19) shows that only one of two nodes can be the parent of the other one at a time for a connected branch, Eq. (20) express that each node can have at most one parent node, and Eq. (21) express the starting node cannot be the parent node for a branch connected to the substation.

3.3. Joint consideration of P2P energy sharing and dynamic network structure

To realize the P2P energy sharing when considering the optimal energy scheduling and actual network operation conditions, the joint optimization model for the P2P energy sharing and dynamic network structure is formulated as follows.

$$Upper\ \ layer: min\ f_i\left(sL_{i,h}, L_{P2P,i_s,i_b,h}, \gamma_{i_s,i_b}(\boldsymbol{\Phi})\right) \tag{22}$$

$$s.t.\ \ Eqs.(3-4, 7-8, 11-14) \tag{23}$$

$$P_{min\_k,h} \le P_{k,h,0} + \sum_{i_s \in N_s, i_b \in N_b} G_{k-i_s,i_b}\boldsymbol{A}_k^T L_{P2P,i_s,i_b,h} \le P_{max\_k,h} \tag{24}$$

$$U_{min} \le U_{i,h,0} + \frac{\partial \boldsymbol{U}}{\partial \boldsymbol{P}}\left|nL_{i,h} - nL_{i,h,0}\right| \le U_{max} \tag{25}$$

$$Lower\ \ layer: min\ \ \Delta P_\Sigma\left(\boldsymbol{\Phi}, \frac{\partial \boldsymbol{V}}{\partial \boldsymbol{P}}(\boldsymbol{\Phi}), G_{k-i_s i_b}(\boldsymbol{\Phi}), \gamma_{i_s,i_b}(\boldsymbol{\Phi}), \Gamma_k\left(nL_{i,h} - (L_{s,i,h}, L_{b,i,h})^*\right)\right) \tag{26}$$

$$s.t.\ \ Eqs.(16-21) \tag{27}$$

In the joint P2P energy sharing model, prosumers' strategies include flexible load and P2P trading energy, DSO's strategies are switches. These two entities have interactive influence during the P2P energy sharing process, which is shown in Fig. 2. For the upper layer, the prosumers aim at reducing power losses arisen from their P2P energy sharing and increasing the local consumption of DERs by adjusting their flexible load strategies, choosing the optimal trading partners, and deciding the amount of P2P trading energy. The LSFs determined by the network structure have an influence on the prosumer's strategies in terms of trading partner and trading energy. For the lower layers, the network operation conditions are affected by the prosumers' flexible load strategies and the P2P energy sharing schedule of the upper layer. By changing the network switch's state, the DSO can dynamically adjust the network power losses, structure, and electrical parameters (i.e., VSCs, PTDFs, and LSFs) to realize the optimal operation conditions while fitting the P2P energy sharing schedule.

It is noted that the prosumers and DSO have the similar goal to optimize the power losses in the network. The power losses taken by the P2P trading prosumers are arising from the P2P trading energy, which is a part of the whole network power losses. The DSO, as a network operator, has the responsibility to reduce the power losses of whole network, while helping the prosumers conduct P2P energy sharing and realizing the maximal comprehensive energy utilization. The comprehensive energy utilization ξ is defined as the comprehensive percentage, which is calculated by the ratio of energy local consumption to PV generation, and the ratio of whole network power losses to the prosumers' netload:

$$\xi = \frac{1}{2}\cdot\sum_{h=1}^{H}\sum\nolimits_{i=1}^{N}\frac{aE_{i,h}}{E_{i,h}} + \frac{1}{2}\cdot\left(1 - \frac{\Delta P_\Sigma}{\sum_{h=1}^{H}\sum_{i=1}^{N}\left|nL_{i,h}\right|}\right) \tag{28}$$

$$aE_{i,h} = \begin{cases} E_{i,h}, nL_{i,h} > 0 \\ L_{i,h}, nL_{i,h} \le 0 \end{cases}, \tag{29}$$

4. Solution algorithm

4.1. Matching process between seller and buyer

The P2P energy sharing model is designed for each seller and buyer, their selling energy and buying energy should match to conduct the P2P energy sharing. Each prosumer optimizes their P2P energy sharing model with some information of other prosumers, and the matching is realized through iteration between prosumers. The matching can be described by the trading matrix, which is shown in Fig. 3.

There are three principles for the matching process:

(1) If the netload $nL_{i,h} < 0$, prosumers must serve as seller, $nL_{i,h} > 0$, prosumers must serve as buyers.
(2) The seller can only sell energy to the buyers and cannot buy energy from other sellers.
(3) The matching is achieved when the selling energy of the seller and the buying energy of the buyer are equal within a certain range.

In the trading matrix $L_{P2P,h}$ of Fig. 3, the column and row represent all the sellers and buyers. Taking the first raw for example, which is for the first prosumer (seller or buyer), each column is the P2P trading energy that this prosumer wants to trade with other prosumers, i.e., for seller 1 is $L_{s,1,i_b,h}, i_b \in N_b$. If this prosumer cannot or refuse to trade with some prosumers (e.g., sellers cannot trade with sellers), the corresponding column will be 0.

The optimization goal is to realize the matching and form the matching-pair, where the trading matrix is expressed as a symmetric matrix when all elements are absolute value. The trading matrix should be updated with the optimization of the P2P energy sharing model, suppose the update index is t and $t \in T$. It is obvious that there is an unmatched energy term sum in the model Eqs. (9) and (10). With the goal of minimizing the model, the unmatched term is hoped to reach 0 through iteration between prosumers, which facilitates the matching processes. The iteration process with the trading matrix update is expressed as follows:

(1) All prosumers have initial strategies to form the initial trading matrix.
(2) Based on the P2P trading information of other prosumers in the previous trading matrix, each prosumer optimizes their own strategies, including flexible load strategies and P2P trading energy schedule, through the P2P energy sharing model, which reflects in each raw of the trading matrix.
(3) The trading matrix serves as the intermediate of the iteration. Once a prosumer's strategies are updated in the matrix, other prosumers will schedule their P2P trading energy based on the updated information. When all prosumers finish their optimization, the first iteration ends, $t = t + 1$, and the whole trading matrix is updated.
(4) If the trading matrix cannot reach a symmetric matrix when all elements are absolute value, repeat steps (2) and (3).

It is noted that the selling energy $L_{s,i_s,i_b,h}$ set by the seller and buying energy $L_{b,i_b,i_s,h}$ set by the buyer cannot be exactly the same even though go through the iteration. Therefore, the error-tolerant rate is proposed to judge the matching, which is determined by the ratio of the difference between buying and selling energy to their minimum one.

$$\varepsilon = \frac{\left| |L_{s,i_s,i_b,h}| - |L_{b,i_b,i_s,h}| \right|}{\min\{|L_{s,i_s,i_b,h}|, |L_{b,i_b,i_s,h}|\}} \times 100\% \tag{30}$$

$$\varepsilon \le \varepsilon_{max} \tag{31}$$

where ε is the error-tolerant rate, ε_{max} is its upper limit of the rate. If Eq. (31) is satisfied, the matching-pair $D(i_s, i_b)$ is built. The algorithm for the load strategies and P2P energy sharing schedule of prosumers are expressed as follows:

Algorithm 1.

1.Input the initial data of prosumers $sL_{i,h,0}, fL_{i,h,0}, E_{i,h,0}$, set the parameters, $\beta_{i,h}$, μ, ε_{max}, T,N.
2.Initialize the prosumers' flexible load strategies $sL_{i,h}$ and the P2P trading matrix $L_{P2P,h,t} = 0$.
3. Prosumer optimize the load strategy and P2P energy sharing schedule.
  For $t = 1$ to$T$
    For $i = 1$ to$N$
      Optimize prosumer i based on Eqs. (9) and (10) and update the $sL_{i,h,t}$ and $L_{P2P,h,t}$.
    End for i
    Calculate the error-tolerant rate ε based on Eq. (30).
    If $\varepsilon < \varepsilon_{max}$
      Calculate the netload of prosumers based on Eq. (2). Prosumers get the optimal load strategies $nL_{i,h,t}$ and the P2P trading matrix$L_{P2P,h,t}$.
    Break
  End If
End for t

4.2. Branch-exchange method for dynamic network structure

The dynamic network structure is uniquely decided by the switches' states, the switches in the distribution network are divided into tie switches and sectionalizing switches, where tie switches are usually open and sectionalizing switches are closed in the initial state. The branch-exchange method is suggested to determine the optimal network structure under the influence of P2P energy sharing.

Through constantly exchanging the switches' states, the set of switches' states that corresponding to the optimal network structure can be selected. The selection process is composed of selecting an exchanged switch, calculating the corresponding power losses when exchange this selected switches' state and determining whether the switches' states should be reserved. Related to the netload and P2P trading energy of prosumers, the details of the branch-exchange method are expressed as follows (Fig. 4).

Firstly, close a tie switch and select a sectionalizing switch as the exchanged switch in a loop. The selected sectionalizing switch is in the lower voltage side of the initially opened tie switch, and next to the tie switch. The selection is aimed at reducing the power losses while fitting the P2P energy sharing schedule, which can be realized if the following two conditions can be satisfied [41]: (i) there is a significant voltage difference across the tie switch, (ii) open the sectionalizing switch at the lower voltage side of the tie switch.

Then, open the selected switch, get the new electrical parameters of the network, and calculate the objective function based on Eq. (15). If changing the selected switch's state can reduce the power losses, which

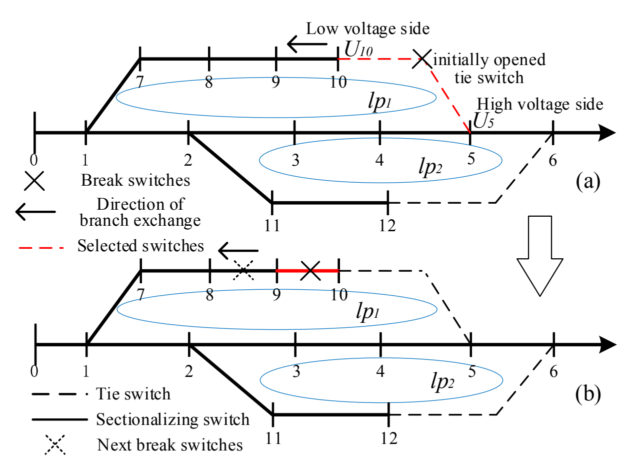

Fig. 4. Process of branch-exchange method.

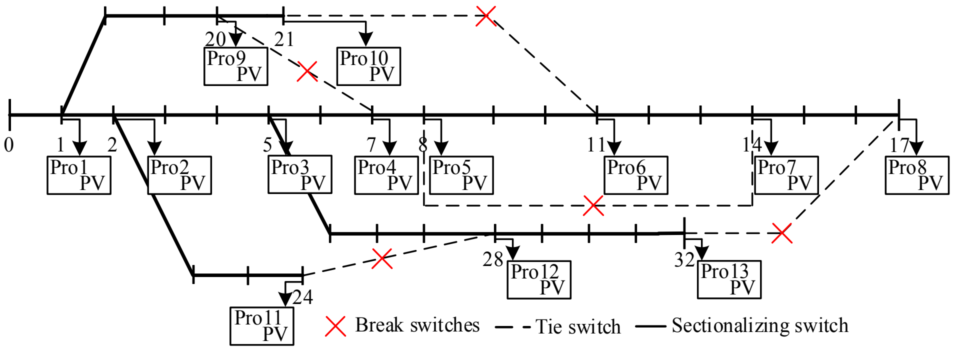

Fig. 5. The initial network structures.

indicates the right direction for reducing power losses, then close this sectionalizing switch and open the next sectionalizing switch on the same side, like Fig. 4 (b) shows. Otherwise, keep the states of the chosen switch in their original states. The process is repeated until the reach the minimum power losses.

The above processes are conducted in each loop. The branch-exchange method is stopped when all loops M are traversed, and the power losses remain unchanged. Then, the last state set of switches is the optimal switches' state and the corresponding network structure is the optimal structure for both network operation and P2P energy sharing. The processes are shown as follows:

Algorithm 2.

1.Input the initial data of the original network's electrical parameters G. set the parameters, lp_m, s_m.
2.Initialize the DSO, calculate the initial power flow to obtain the $P_{k,h,0}$, $U_{i,h,0}$, and $P_{loss,0}$ based on the information of prosumers $sL_{i,h,0}$, $fL_{i,h,0}$, $E_{i,h,0}$.
3. DSO optimize the switches $\mathbf{\Phi}$ (i.e., dynamic network structure) based on the prosumers' information, i.e., $nL_{i,h,t}$ and $L_{P2P,h,t}$.
For $m = 1$ to M
Determine the high/low voltage side of the tie switch, then select the sectionalizing switch to close.
For $s_m = 1$ to S_m
Open the selected switch and calculate the power losses $\Delta P_{\Sigma,s_m}$ based on Eq. (15).
If $\Delta P_{\Sigma,s_m} < \Delta P_{\Sigma,s_{m-1}}$
Close this sectionalizing switch and select the next sectionalizing switch in the same side.
Else
Keep the state set of switches in the original states.
Break
End If
End For s
End For l

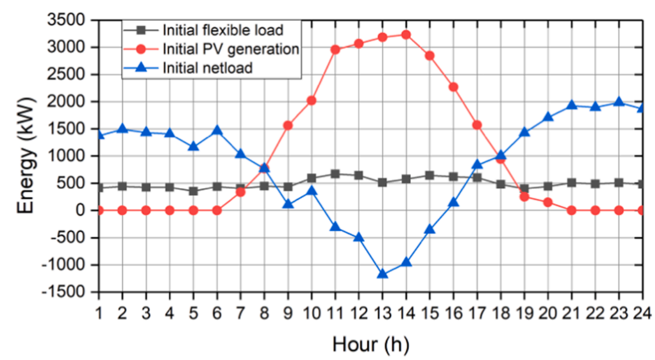

Fig. 6. The initial flexible load distribution, netload distribution, and PV generation of prosumers.

Algorithm 3..

1.Based on the initial value of algorithms 1 and 2, conduct this algorithm.
2.***For*** *iter* = 1 to *Itermax*
(1) DSO broadcast the initial (the index is 1) switches' state $\mathbf{\Phi}_1$, node voltage $U_{1,i,h}$ and the active power flow $P_{1,k,h}$ to prosumers.
(2) Based on the initial network structure, prosumers perform the algorithm 1. Get the load strategies $nL_{i,h,iter}$, P2P trading matrix $L_{P2P,h,iter}$ of all prosumers, and broadcast to the DSO.
(3) Based on the prosumers strategies, DSO perform the algorithm 2, get the switches' state $\mathbf{\Phi}_{iter}$ (i.e., dynamic network structure).
(4) ***If*** $\mathbf{\Phi}_{iter} = \mathbf{\Phi}_{iter-1}$
Break
Else
Update the network structure and return to step (2).
End If
End For *iter*

4.3. Solution process for the joint P2P energy sharing model

The joint P2P energy sharing model Eqs. (22)–(27) is a nonlinear mixed-integer programming (NMIP) problem. There are two challenges to solve the problem: (i) The decision variables of the P2P energy sharing process and dynamic network structure process are respective continuous and discrete variables, which is difficult to a joint decision by mathematical methods. Besides, Although the P2P energy sharing is conducted day-ahead, the time interval is set as one hour, while the dynamic network structure model is set as daily [42]. Therefore, the time scale of the decision is different between these two processes. These two factors result in the joint P2P energy sharing model cannot be solved simultaneously. (ii) The P2P energy sharing process is coupled with the dynamic network structure process and cannot be separately solved. To deal with these two difficulties, the iteration solution algorithm between the matching method and the branch-exchange method is proposed. The details of the algorithm are shown as follows:

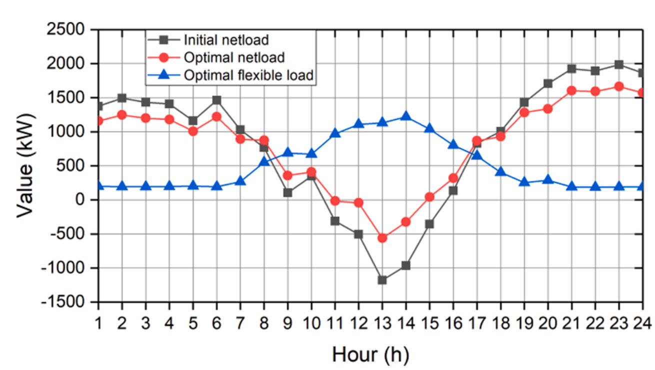

Fig. 7. The optimal load strategies of prosumers.

Table 1
Partial derivative that determines the LSFs.

Node/prosumer	1/1	2/2	5/3	7/4	8/5	11/6	14/7	17/8	20/9	21/10	24/11	28/12	32/13
LSF	−0.630	−0.839	0.124	0.087	0.036	−0.029	−0.006	−0.001	0.047	0.028	0.131	0.163	0.089

5. Case study

5.1. Basic data

The IEEE 33-node test network is used as the network topology in this paper, which structure is shown in Fig. 5. The network distribution factors (i.e., VSCs $\frac{\partial V}{\partial P}$, PTDFs G_{k-i_s,i_b}, LSFs γ_{i_s,i_b}) are calculated by the network parameters. 13 prosumers access to some nodes of the network except the balancing node, and the data of the prosumers are taken from an industrial park in Guangdong Province, China. The initial flexible load distribution, netload distribution, and PV generation are shown in Fig. 6. Prosumers in the network is equipped with the UEMS and can choose the role of seller or buyer to participate in the P2P energy sharing according to their netload. The time interval for P2P energy sharing is one hour, and the time scale is one day (i.e., $H = 24$). The network structures are daily dynamically changed in the P2P energy sharing process by the DSO, and the time difference is solved by the hourly weighted sum of the P2P energy sharing schedule. The parameters of prosumers $\beta_{i,h}$, μ, $sL_{i,h,max}$, and $L_{P2P,max}$ are respectively set as 1, 10, 200 kW, and 300 kW, and the parameters of network operation $P_{max\_k,h}$, U_{min}, U_{max} are respectively set as 500 kW, 0.95p.u., and 1.05p.u.

5.2. Analysis of the prosumers' strategies

5.2.1. Results of load distribution

The optimal strategies of flexible load and netload are shown in Fig. 7. The overall netload distribution that should be traded with the utility grid is optimized and realized the peak load shifting. The flexible load in time slots 1–8 and 18–24 with less PV generation is shifted to the time slots 9–17 with high PV generation, reducing the peak of selling energy to the utility grid. Meanwhile, the peak load in time slots 1–7 and 20–24 are also reduced by the optimal flexible load strategies. For sellers, the peak load shifting increases the DERs' local consumption, while for buyers, gathering energy in the high PV time slots can facilitate P2P energy sharing. This happens because of the P2P energy sharing model (9–10), where prosumers aim at minimizing the trading energy with the utility gird.

5.2.2. Results of P2P trading energy and partners

The P2P trading schedule of the prosumers mainly relates to the load strategies and LSFs, which is calculated by the partial derivative of the network losses with respect to the active power of each node is computed to obtain the LSFs. The partial derivative that determines the LSFs is shown in Table 1. There are 24 trading matrices in 24 h, the optimal P2P trading matrix of time slot 11 is shown in Fig. 8. The trading partners of each prosumer and the amount of trading energy can be obtained from this matrix. The negative value in the diagonal element means this prosumer is a seller, and positive means buyer. It is obvious that each prosumer has at least one trading partner, most of prosumers have three and more than three trading partners. The P2P trading partner selection is a coupled process, which is affected by all the prosumers. Take seller 1 for example, the trading partners are buyers 2, and 3, and the LSFs are respective 0.209, and 0.754. The P2P energy sharing is mainly happened with buyer 2 due to the minimal LSFs. The selection of the other two trading partners is affected not only by seller 1, but the trading partners of buyer 3, which is further affected by other sellers, like 4, 5, 11 and 13.

The total P2P trading energy of each prosumer is limited by their netload strategies, which are optimized with the P2P trading energy at the same time. The results of Fig. 8 show the matching between sellers and buyers. The trading energy is also determined by the LSFs, while interactively affected by all prosumers trading partners and energy. Fig. 9 shows the energy that trading with the utility grid of all prosumers in 24 h. From Fig. 9, the trading energy with the utility grid is significantly decreased through the P2P energy sharing, especially in the time slots with high PV generation, help the energy local consumption, and reduce the impact of flexible DERs on the system operations.

5.3. Results of the dynamic network structure

The optimal network structure is shown in Fig. 10. The set of switches is changed from $\Phi_0 = \{7-20, 8-14, 11-21, 24-28, 17-32\}$to

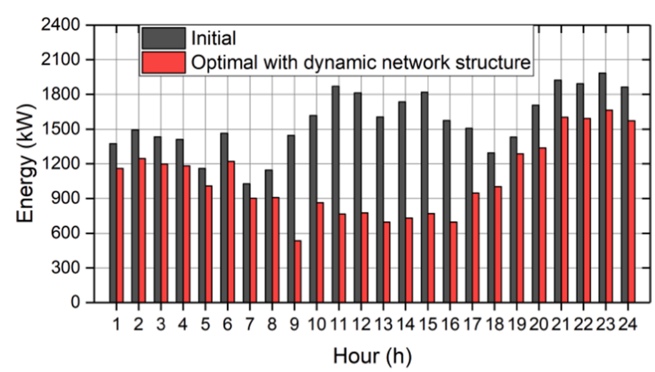

Fig. 9. Trading energy with the utility grid.

	Seller1	Buyer2	Buyer3	Seller4	Seller5	Buyer6	Buyer7	Buyer8	Buyer9	Seller10	Seller11	Buyer12	Seller13
Seller1	-70.91	56.89	11.47	0.00	0.00	0.53	0.00	0.53	0.54	0.00	0.00	0.95	0.00
Buyer2	-56.89	60.15	0.00	-0.47	-0.37	0.00	-0.07	0.00	0.00	-1.11	-0.52	0.00	-0.74
Buyer3	-11.47	0.00	90.06	-14.84	-32.29	0.00	-0.06	0.00	0.00	-1.09	-16.94	0.00	-13.37
Seller4	0.00	0.48	14.83	-66.15	0.00	19.44	0.00	5.59	14.50	0.00	0.00	11.31	0.00
Seller5	0.00	0.36	32.29	0.00	-132.54	14.81	0.00	10.41	1.31	0.00	0.00	73.36	0.00
Buyer6	-0.53	0.00	0.00	-19.44	-14.81	83.16	-6.05	0.00	0.00	-0.54	-17.21	0.00	-24.57
Buyer7	0.00	0.00	0.00	0.00	0.00	5.95	-6.34	0.00	0.39	0.00	0.00	0.00	0.00
Buyer8	-0.57	0.00	0.00	-5.59	-10.41	0.00	-0.02	44.96	0.00	-0.54	-12.58	0.00	-15.25
Buyer9	-0.54	0.00	0.00	-14.50	-1.31	0.00	-0.53	0.00	61.88	-0.57	-20.55	0.00	-23.89
Seller10	0.00	1.11	1.10	0.00	0.00	0.54	0.00	0.53	0.57	-4.38	0.00	0.54	0.00
Seller11	0.00	0.53	16.94	0.00	0.00	17.21	0.00	12.57	20.55	0.00	-86.88	19.08	0.00
Buyer12	-0.97	0.00	0.00	-11.31	-73.29	0.00	-0.08	0.00	0.00	-0.54	-19.08	124.83	-19.56
Seller13	0.00	0.71	13.37	0.00	0.00	24.57	0.00	15.25	23.89	0.00	0.00	19.56	-97.35

Fig. 8. Optimal trading matrix in time slot 11.

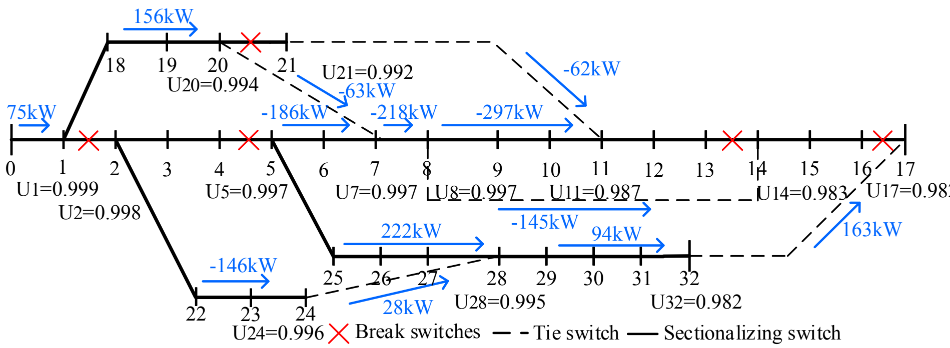

Fig. 10. The optimal network structures.

Table 2
The results of power losses, energy load consumption and comprehensive energy utilization.

Scenarios	Initial	Optimal	Percentage increase
Power losses of whole network	56.41 kW	22.10 kW	60.8%
Energy local consumption	16377.40 kW	22816.07 kW	39.3%
Comprehensive energy utilization	80.02%	94.36%	17.9%

$\Phi = \{1-2, 4-5, 13-14, 16-17, 20-21\}$ to obtain the minimum power losses. Besides, Fig. 10 also shows the node voltages that prosumers access and power flow in time slot 11. It is clear that all node voltages and branch power flow are within the normal operating range of the network. Because of the dynamic network structure, the transmission power line is changed with the switch's states, affecting the P2P energy sharing processes. For example, according to Fig. 8, prosumer 8 is a buyer in time slot 11 and access to node 17. The trading partner of the buyer 8 is sellers 4, 5, 11, and 13, who access node 7, 8, 24, and 32, respectively. The P2P energy sharing is realized through the path 17–32-31–30-29–28-27–26-25–5-6–7-8, and 17–32-31–30-29–28-24. However, buyer 8 cannot trade with seller 10 that access node 21, because the electrical line between these two prosumers is longer and the power losses is more than others.

5.4. The effectiveness of joint P2P optimization model

According to the initial and optimal netload distribution, the energy local consumption, power losses of whole network, and comprehensive energy utilization of initial and optimal scenarios are shown in Table 2. Through the optimization, the energy local consumption increases 4877.4 kW, the power losses decrease 34.31 kW, and the comprehensive energy utilization improves 14.1%. The reasons for these changes can be analyzed from the prosumers and DSO.

On the prosumers' side, on one hand, for each prosumer, the flexible load is transferred to the time slots 11–15 with surplus PV generation (Fig. 7 shows), resulting in the reduction of buyers' buying energy from the utility grid in time slots 1–11 and 15–24. The amount of active power that should sell to the utility grid is also reduced in time slots 11–15 due to the flexible load shifting. On the other hand, the P2P energy sharing between each prosumer further facilitate the energy local consumption to a greater extent. Therefore, the energy local consumption can be enhanced, while the power losses arisen from P2P energy sharing is also optimized for each prosumer.

On the DSO's side, the power flow changed by the P2P energy sharing may change the whole network power losses. Based on the joint optimization model of P2P energy sharing and dynamic network structure, the power losses of whole network are decreased by changing the switches' state, e.g., shortening the electrical distance of power

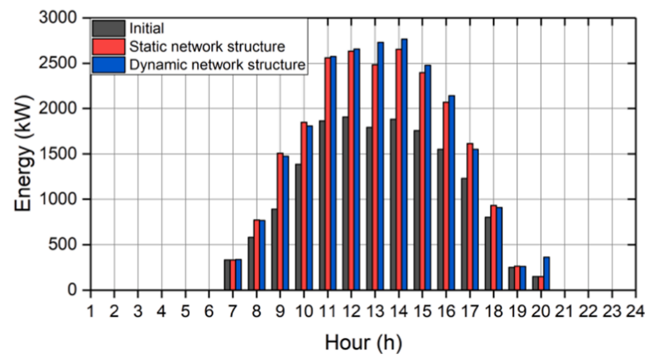

Fig. 11. Energy local consumption of all prosumers.

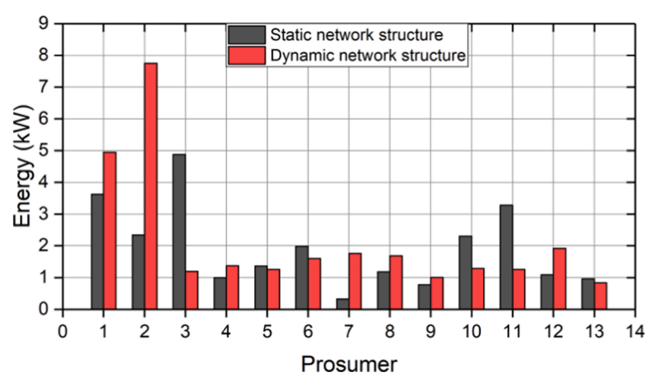

Fig. 12. The power losses of each prosumer.

transmission, and the network operation condition for P2P energy sharing is also optimized. According to the Eqs. (28) and (29), higher comprehensive energy utilization can be obtained when increase the energy local consumption and reduce the whole network power losses.

5.5. Comparing with the P2P energy sharing with static network structure

To demonstrate the effectiveness of considering dynamic network structure in the P2P energy sharing. The joint optimization that combines the P2P energy sharing and network structure is compared with the static network structure.

Fig. 11 shows the energy local consumption of all prosumers and Fig. 12 shows the power losses of each prosumer. It is clear that the energy local consumption is greatly increased though the energy scheduling. Compared with static network structure, the energy local consumption is increased from 22214 k.5 W to 22816 k.1 W while the power losses of all prosumers are increased from 25.1 kW to 27.8 kW under the scenario of dynamic network structure. It is noted that the

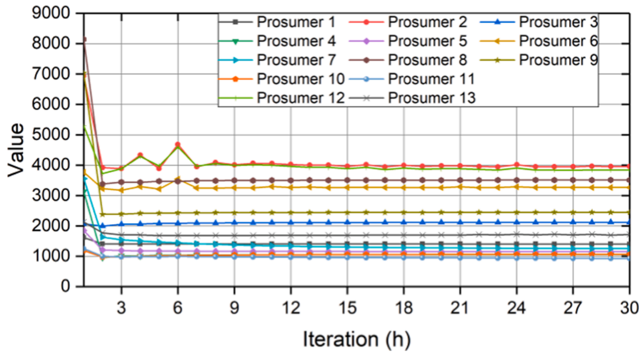

Fig. 13. Convergency process of P2P energy sharing.

dynamic network structure can facilitate the P2P trading energy, so that increase the power losses caused by P2P energy sharing. Meanwhile, the whole network power losses are decreased from 32.73 kW to 22.10 kW through the dynamic network structure, which shows the effectiveness of dynamic network structure in terms of optimizing P2P energy sharing and network operation.

The P2P energy sharing schedule (i.e., the amount of P2P trading energy and partners) and network structure are jointly optimized to realize the optimal network operation conditions. In the scenario of dynamic network structure, the operation conditions in the physical layer can be changed to respond to the P2P energy sharing schedule. The switches' state is changed from the initials state to obtain a better network structure that supports the optimal energy schedule of prosumers, while providing better network operation conditions with minimal power losses and maximum comprehensive energy utilization. However, in the static network structure, the DSO cannot adjust their network structure to fit the P2P energy sharing while reaching a better operation condition, which may result in the deviation of the optimal solutions for both prosumers and DSO.

5.6. *Analysis of practical feasibility*

The proposed solving algorithm is implemented in a distributed way with two kinds of iterations. The first is among P2P trading prosumers, which will go through 26 iterations, and the convergence curve is shown in Fig. 13. The second is between DSOs and prosumers, the iterations number is 3. As only a few bytes of data are exchanged between different prosumers and DSOs, the proposed P2P energy sharing model can be implemented in the existing infrastructure of the smart grid. The data communication is over the wireless channel in private 4G/5G network with Virtual Private Network (VPN) as reference [39] shows. The UEMS of prosumers optimize the load strategies and the servers in the DSO help calculate the dynamic network structure. Besides, the dynamic network structure controlled by the switches' state can be realized by the high-speed switching devices. The devices are generally made of power semiconductor, such as insulated gate bipolar translator (IGBT) [43], MOSFET [44], and can be used to achieve fast transient response, which minimizes the time taken to change the system operation state.

6. Conclusion

In this paper, a P2P energy sharing framework considering dynamic network structures is proposed, which is solved by the designed solution algorithms with matching process and branch-exchange methods. A test system with realistic data from a demonstration project is used to obtain the numerical results. The optimal P2P energy sharing schedule and load strategies of prosumers can be determined accompanied with the optimal network structure for operation. Based on these optimal strategies, the power losses are decreased by 60.8%, and trading energy with the utility grid is transferred to the P2P energy sharing, reducing the impact of the DERs on the system operation while increasing the energy local consumption 39.3%. The comprehensive energy utilization defined in this paper also increase 17.9% through the joint optimization. Besides, the dynamic network structure is compared with the static network structure to show the effectiveness of dynamic network structure. It shows that incorporate the DSO's switches strategies can get the better results for prosumers and DSOs, reducing the power losses of whole network 32.4% while increase he energy local consumption 2.71%. Future work will relate to deeply explore the joint optimization of the user side and network side and reveals the coupling mechanism of the entities in these two sides.

CRediT authorship contribution statement

Liudong Chen: Conceptualization, Methodology, Software, Writing - original draft. **Nian Liu:** Conceptualization, Methodology, Supervision, Funding acquisition. **Chenchen Li:** Conceptualization, Methodology, Software, Writing - original draft. **Silu Zhang:** Methodology, Writing - review & editing. **Xiaohe Yan:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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