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Peer-to-Peer Electrical Energy Trading Considering Matching Distance and Available Capacity of Distribution Line

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Abstract: The concept of peer-to-peer (P2P) energy trading leads to the flexible energy transaction of prosumers and consumers, for which the P2P business model is normally the main attention. It still requires system operators to address the challenges in trading and constraint problems. In this context, this work regards the congestion constraint in conjunction with energy trading. Firstly, a matching approach based on the cost path is proposed. It is consistent with the cost for the dispatch along each route, making a suitable matching in both distance and bids. In combination with the matching process, the available capacity has to be considered to avoid line congestion. Secondly, the bus transfer factor (BTF) and the partitioning zone approach are proposed to overcome the issue. BTF refers to a response of bus power to the congested line power. The partitioning zone, separated into the source and the load area, enables a simple management strategy. Thereby, the power adjustment in each area follows BTF. Moreover, compensation and opportunity cost are discussed. In comparison with the demand-side reprofiling approach, this work creates more trading chances for buyers and sellers by 24.70% and 30%, respectively. The reason is traders do not have to curtail their power unnecessarily for congestion management.

Keywords: peer-to-peer energy trading; electricity energy market; matching approach; congestion management

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1. Introduction

1.1. Background and Motivation

Traditionally, power flows a single way from the transmission level to the distribution level, and all operations are managed at the transmission level. It is the unique direction resulting in the energy-trading occurrence within only the transmission system. The electricity authority purchases electricity from private producers and distributes it to customers. Currently, with the rapid development of distributed energy resources (DERs) such as household solar rooftops and electric vehicles in the distribution system, consumers have produced electricity and sold the surplus electricity to the utility grid and neighbors, which constitutes prosumer behaviour. The prosumer can trade electricity in multi-direction trading within the local area [1]. As a result, peer-to-peer (P2P) energy trading occurs in the distribution network. It can be classified into three different structures [2]: full P2P, hybrid P2P, and community-based market. In full P2P, peers can trade power with neighbors directly. A community-based market [3] refers to energy trading from peer to peer via a community co-ordinator who acts as a co-ordinator or operator and exchanges information among the market players. Moreover, a peer can choose to trade in terms of full P2P or community-based market for hybrid P2P. The operator considers the market overview to manage the trading effectively. Otherwise, the direct trading between peers could possibly create problems for the overall market. Hence, this work focuses on the P2P community-based market, which defines two operators, the market operator (MO) and the distribution system operator (DSO), to manage transactions. The MO manages the matching process, market pricing process, and compensation. The DSO manages the congestion problem based on the available capacity of the distribution line and sends traders the results via MO.

Many P2P projects such as Piclo, Vandebron, SonnenCommunity, Brooklyn Microgrid, and PeerEnergyCloud are implemented. In [4], Piclo in the United Kingdom is a P2P energy-trading platform based on preferences and locality. The Vandebron platform in the Netherlands is an energy supplier for trading between consumers and prosumers. In addition, SonnenCommunity in Germany is a P2P energy-trading platform by using battery storage technology [5]. Brooklyn Microgrid creates a blockchain for a P2P energy trading platform [6]. In [7], PeerEnergyCloud in Germany designs a cloud-based technology for local electricity trading. The study in [8] compared the distributed generation trading mechanisms—market structures, connection classifications, economic benefits, and practical issues—in the UK and China. Definitely, the trading mechanism is different in each country. Nonetheless, there are many challenges in P2P energy trading. The main factor for efficient energy trading is market designing, including the transaction part and the network constraint consideration part.

The challenges in the transaction part are how peers should be matched for the matching process and how the clearing price should be defined for the market pricing process. The matching process is important because it is the beginning of the P2P transaction process. P2P energy trading is not entirely independent from the grid. Power must be transferred over the grid line. Thus, an additional service fee for the usage of the transmission and distribution lines should be considered. The additional fee, a type of operating cost, relates to the electrical distance. In [9], at least 60% of the U.K. electricity bill is the service charge, with approximately 22% related to the distance charge. The greater the electrical distance is, the more the power loss is. Accordingly, the additional fee is also higher. It can be defined by the physical distance between peers. To reduce the additional fee, the traders should also match based on distance. Note that the additional fee or cost path is not added to the settlement bill for this work. It is used as a reference for the proposed matching process. In the network constraint consideration part, the high penetration of DERs in a local area leads to the increasing of power in the distribution line. Possibly, a congestion problem may occur in the distribution line. The transactions can be removed if they violate the system constraint. Therefore, the concern should be regarded.

1.2. Relevant Literature Review

P2P electrical energy trading can be explained in two parts. These are the transaction part, included matching and the market pricing mechanism, and the network constraint consideration part. The study in [10] describes a four-layer system architecture of P2P energy trading; this work focuses on the business layer from the bidding process to the settlement process. In the transaction part, sellers and buyers can be matched by voluntary matching, the double-auction approach, and conditional matching. However, voluntary matching based on negotiation is hard to control. Some works in research present the double-auction mechanism for matching and setting the clearing price. A k-factor continuous double auction is proposed in [11]. Many kinds of auction-based approaches for market clearing are compared in [12]. Furthermore, the study in [13] proposed the closest energy-matching (CEM) double-auction mechanism to match each buyer with the seller whose available surplus energy is closest to the amount requested by the buyer. Those show that the double-auction mechanism is economically consistent and less complex computationally due to it being only based on arranging the offering and bidding price. Absolutely, the price sorting results in a satisfying clearing price for the traders. The sellers can sell electricity at a price no lower than the offering price and the buyers can buy it at a price no higher than the bidding price. Nonetheless, the trading pair from this mechanism is considered from only the price regardless of the technical factors. In the actual dispatch, another parameter, such as distance, should be considered for the matching process. It directly affects the system operation, especially the power loss and operating cost, which leads to a conditional match. An interesting conditional matching example is to address the cost path problem. The matching method based on the minimal electrical distance approach is suggested in [14] to reduce network losses and network charges. The optimized path algorithm named the slime-mould-inspired optimization method for addressing the problem of matching is proposed in [15]. The study in [16] proposed a P2P optimization method to match two parties by decreasing the distance of their energy trading. The study in [17] described the Power Transfer Distance (PTDF) and Thevenin's impedance distance approach to calculate the electrical distance. However, PTDF is appropriate for mesh networks such as transmission level. The study in [18] proposed a grid service charge calculated based on the electrical distance between agents to incite them to trade with their closest neighbors in order to reduce power losses. This results in the trading not being liberated because it obstructs trading with farther peers. The study in [19] proposed two market mechanisms: the stable matching mechanism and the continuous double-auction-based mechanism for P2P energy trading driven by the electrical distance calculated based on Thevenin's impedance distance approach. Moreover, the study in [20] describes various electrical distance measurement methods: Thevenin, Mutual Impedance Distance, PTDF, Jacobian distances, and Topological Geodesic Distance. When the traders are independent in their offer bid and power, only the distance consideration for the matching may not be appropriate for P2P energy trading. Moreover, it is possible that the return from the matching based on distance is lower, although the seller matches with the closest buyer. The reason is ignoring the bids. As well, the return is less if the power is transmitted over a longer distance. The operator has to define the proper matching by considering both the distance and bid. Hence, the cost path is employed as a proposed matching criterion for this part.

In the network constraint consideration part, the possible impacts of local energy trading on utility in the network power flow and voltage are analyzed in [21]. One of the interesting problems is line congestion. Therefore, an optimization strategy with a different constraint is suggested as a method of alleviating line congestion. The study in [22] proposed a congestion management method under the P2P energy trading of microgrids based on a co-operative game strategy. Additionally, the study in [23] proposed a sensitivity analysis to assess the impacts of P2P transactions on the network. The optimization method is more complex because it takes into account the constraints in calculating the optimization together with trading. To simplify, the constraints should be excluded from the trading process. The study in [24] compared different methods to comprehensively deal with the transmission and distribution congestion for different electricity market models such as developing new transmission lines, system rescheduling, and the direct/indirect control method. Nonetheless, the technical method of developing new transmission lines increases investment in the power grid. The study in [25] presented the forced direct and indirect solutions; however, the indirect solution is appropriate for P2P energy trading. Examples of indirect solutions are dynamic tariff (DT) [26] and dynamic tariff subsidy (DTS) [27]. The study in [28] allocates a grid tariff on the trades causing congestion, which convinces peers to avoid congested paths until a consensus solution satisfies both sellers and buyers. The study in [29] presented the dynamic tariff, reconfiguration, and re-profiling product for solving a congestion problem. DSO should solve this problem in terms of an indirect solution by the incentive mechanism to persuade the market participants to adjust their power profiles. When a peer in each power bus adjusts their power, it has an unequal impact on the power on the congested line. A factor that reflects a line response to the power adjustment in the power bus is called BTF. It shows how much a peer in each power bus should adjust their power in order to eliminate the congestion. Furthermore, the partitioning zone approach is used to define who should increase or decrease power to manage power in the congested line based on a management area. The study in [30] proposed transaction zones to satisfy consumer demands and avoid network congestion. That means the operator intervenes in the trading from the beginning. In liberated trading, the traders should trade the total electricity as needed first. Hence, it is better for the DSO to intervene to manage the problem later during only the troubled period. The study in [31] described redispatch schemes: equal partitioning, merit order, and PTDF for partitioning among the power plants inside the source and load area. The management area consisting of the source and load area is deployed, using the proposed power adjustment. Thereby, the power adjustment based on BTF and the management area is proposed. As well, the operator compensates to the traders who participate in the congestion solution.

1.3. The Main Contributions of This Work

With the above-mentioned research, to simplify and complete trading, this work will regard the constraint in conjunction with the transaction part by the proposed approach. The major contributions of this work are summarized as follows:

i. The matching approach based on the cost path is proposed, making a suitable matching in both distance and bids.
ii. The line congestion management using BTF and partitioning zones is proposed for power adjustment in order to avoid unnecessarily curtailing traders' power.

1.4. Structure of This Work

The rest of this work is organized as follows. An overview P2P community-based market is described in Section 2. Then, the proposed matching approach and basic market pricing in the MO mechanism are described in Section 3. Additionally, the DSO mechanism for congestion management, re-profiled using BTF and partitioning zones, is explained in Section 4. Next, the compensation for the congestion solution is explained in Section 5, while the case study and result are presented in Section 6. Finally, Section 7 concludes the whole of this work.

2. Overview P2P Community-Based Market

A P2P community-based market that requires the operators, MO and DSO, for trading is proposed as shown in Figure 1. There are sellers, buyers, the MO, and the DSO. The sellers and buyers can consume and produce the electricity from renewable energy, which are served as prosumers. Additionally, the MO and the DSO are responsible for the trading process and the constraint consideration process, respectively.

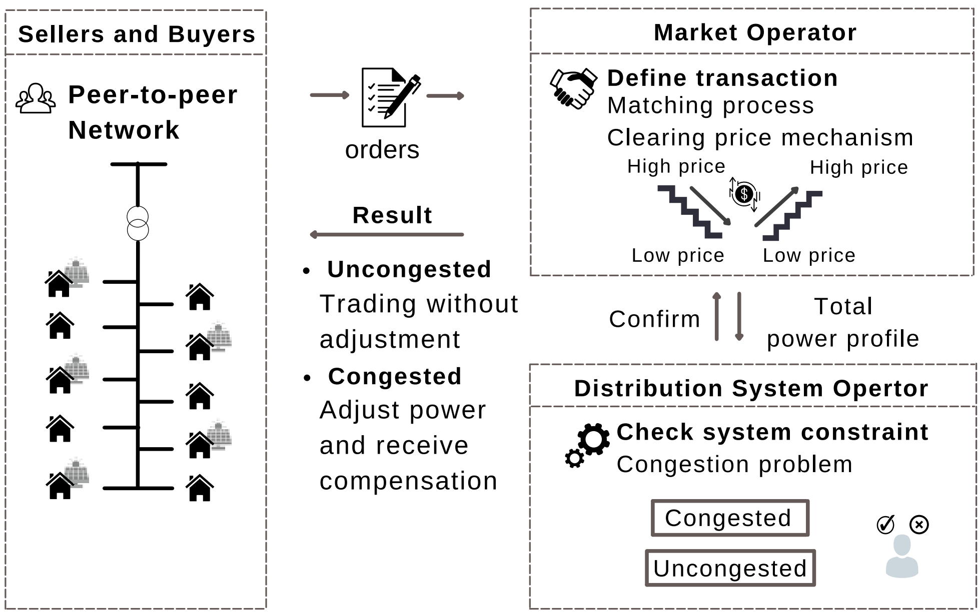

Figure 1. The role of players and overview processes in P2P community-based market.

For the trading process, each trader sends the MO an order that includes power and price to define who can trade in P2P energy trading. The MO is like a platform for managing the transactions such as defining the clearing price, verifying the transactions, and the compensation. It also sets the rules of P2P energy trading. After the MO has received all orders from traders, the MO then defines the P2P participants who can trade in P2P energy trading. It is defined using the concept of price sorting in the step function. In detail, the offering price means the lowest price that sellers are willing to sell at, whereas the bidding price means the highest price that buyers are willing to buy at. If the offering price is not higher than the bidding price, there will be satisfaction for both sides. Thereby, they can trade in P2P energy trading, called P2P participants. Other traders are called the un-participants. Instead, they need to trade with the utility grid. After defining the P2P participants, the MO will define the transactions by the matching process and clearing price mechanism. For the proposed matching approach, the distance factor and cost path are presented. After the matching process, the clearing price mechanism which served as an average mechanism is used for defining the clearing price. The clearing price or P2P price in each trading pair is between the offering price and the bidding price. As well, it is not higher than the electricity-grid rate.

When the matching process and defining clearing price process are finished, the MO sends the DSO the total power profiles for checking the system constraint. A system constraint for this work is the congestion problem. With emerging trading in the local level, it possibly increases the power in the distribution line, causing line congestion. Thereby, the DSO manages this problem according to the proposed approach. The DSO will send traders the results via the MO. In the congestion problem occurrence case, the results include the way to adjust their power for the removal of the congestion problem. Hence, the re-profile using BTF and partitioning zones is implemented.

When this problem is cleared, the DSO will permit peers to trade. Then, the power trading occurs between the seller and the buyer. With the power adjustment, the MO will compensate to peers who participate to adjust their power; it persuades them to solve this congestion problem. If a congestion problem does not occur, the DSO will allow the traders to be able to trade power immediately.

3. Proposed Matching Approach and Basic Market Pricing in MO Mechanism

This section explains the MO mechanism. The MO is responsible for matching and defining the P2P price. In the proposed matching process, it is based on the cost path which is the additional fee or cost for the dispatch in each power route. The buyer's bidding price is used as a unit price for calculating the cost path. The power from the seller can flow to the buyer through many routes. To reflect the result of distance, the nearest route is used for calculating a distance factor. After the matching process, the MO defines the clearing price described in this section as well.

3.1. Proposed Matching Approach

In the first step of the matching process, the MO will define who can participate in P2P energy trading. All traders submit their orders, power and price, to the system. The seller offers the lowest price that they are willing to sell at and the buyer bids the highest price that they are willing to buy at. The offering price is sorted in ascending order in the step function, whereas the bidding price is sorted in the opposite way. If the offering price is not higher than the bidding price, they can trade in P2P energy trading according to the satisfaction of both sides, and they are called P2P participants. If the offering price is more than the bidding price, they cannot trade in P2P energy trading, and they are called un-participants. They have to trade electricity with the utility grid instead; otherwise, they cannot trade their electricity.

The participants will be matched once the MO has finished determining who are allowed to engage in P2P energy trading. The further the distance is, the more power loss is. Thereby, the distance between nodes is an important factor and the traders should be matched with the right distance. In this work, the cost path is proposed as a matching criterion. The MO considers the cost path that is calculated from the distance factor and bidding price. The shortest distance that may be travelled to deliver power to a load is used to compute the distance factor. However, the MO defines the path to be a base for the cost calculation; it is not the actual flowing path. The distance factor ($DF_{i,j}$) is expressed as follows:

$$DF_{i,j} = \frac{The\ shortest\ cumulative\ distance}{Total\ shortest\ distance\ in\ all\ path} \quad (1)$$

With the above-mentioned formula, a unit price for calculating the cost path is the bidding price of buyer j (b_j). Because the dispatch occurs for the buyer's demand response, the cost path value varies based on the buyer. Hence, the cost path ($CP_{i,j}$) is expressed as follows:

$$CP_{i,j} = DF_{i,j} \times b_j \quad (2)$$

The inexpensive selling price creates more benefits for the traders. Therefore, in the process, the MO will calculate the cost path to find a pairing for the seller who offers the lowest offering price to the seller who offers the highest offering price, respectively. To calculate the distance factor of the first seller, the MO defines the possible lowest distance for the dispatch to each buyer. The physical distance is computed by summing the lengths of the power lines between nodes; moreover, a distribution transformer between paths is regarded as a node. In order of the possible matching, the proportion of the shortest cumulative distance to the total distance is the distance factor value. Then, the bidding price of each buyer is multiplied with the factor as the cost path. That means the number of cost path data equals the number of buyers. The first seller should be matched with the buyer who results in the least-cost path. This is the end of the process for the first seller. Next, the MO will find a pairing for the next seller who offers the next lowest offering price. For other sellers, this process is repeated until every seller is matched. Instead, if the buyer has been already matched, the seller has to match with another buyer who causes the next least-cost path. In the power part, if the seller has the rest of the power to sell, it is sold to another buyer who causes the least-cost path. Moreover, if the seller does not have enough power to sell, the buyer has to buy the rest of power from another seller based on the least-cost path. By the proposed matching mechanism, the power from the seller is dispatched to the buyer with the appropriate distance and cost.

To explain the total process, the example network, the power line length or distance between two nodes, and other details of the traders are presented in Figure 2. In this network, there are six nodes that include three sellers labelled as A, B, and F as well as three buyers labelled as C, D, and E. The offering price and bidding price are shown in the figure as well. By price sorting, all traders can trade in P2P energy trading. The priority of the seller is A, B, and F, respectively. Hence, the matching process begins with finding a pairing for the seller A who offers the lowest offering price. The shortest distance from A to C, D, and E are 15, 10, and 20, respectively. The shortest distance from B to C, D, and E are 9, 17, and 5, respectively. The shortest distance from F to C, D, and E are 22, 17, and 13, respectively. Therefore, the distance factors in (1) are expressed in Table 1. Furthermore, the cost paths in (2) are expressed in Table 2. With the least-cost path of each seller, seller A matches with buyer D, seller B matches with buyer E, whereas seller F matches with buyer C. However, for example, if the power supply of seller A is more than the demand of buyer D, seller A has to sell the rest of their power to buyer C and buyer E, respectively. This is based on the order of the cost path in ascending order.

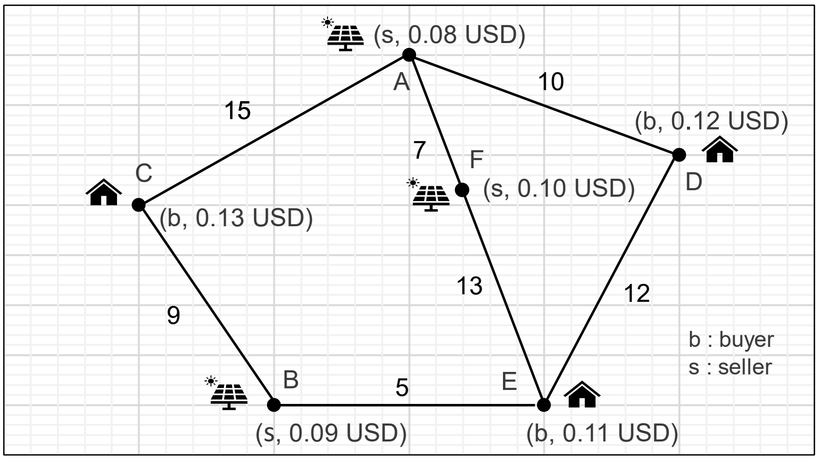

Figure 2. Example network for the proposed matching process.

Table 1. The calculation example of distance factors.

Buyer \ Seller	A	B	F
C	15/45	9/31	22/52
D	10/45	17/31	17/52
E	20/45	5/31	13/52

Table 2. The calculation example of cost paths (USD/kWh).

Buyer \ Seller	A	B	F
C	0.043	0.038	0.055
D	0.027	0.067	0.039
E	0.049	0.018	0.028

3.2. P2P Pricing Based on the Average Mechanism

After the matching process, the MO defines the clearing price for each pair by the average mechanism. The clearing price is called the P2P price (P_{P2P}). It is calculated from the average of the offering price and bidding price in each pair as follows:

$$P_{P2P} = \frac{1}{2}\left(a_i + b_j\right) \tag{3}$$

where a_i is the offering price and b_j is the bidding price.

The P2P price in (3) from the average mechanism is between the offering price and bidding price in each pair. It follows individual rationality, a balanced budget, and economic efficiency [32]. The seller and buyer will trade power with a satisfactory clearing price. It is not too cheap to sell for the seller and it is not too expensive to purchase for the buyer. Moreover, it creates fairness for the seller and buyer because the total revenue of the seller is equal to the total cost saving of the buyer. The revenue for the sellers refers to a return from the average price compared with trading at their offering price. Normally, the P2P price is more than the offering price. That means the sellers can sell power at a higher price than they intend to. Hence, a return from trading at the average price is more than trading at the offering price, resulting in the revenue. The cost saving for the buyer refers to an expense compared with trading at the bidding price. Normally, the P2P price is less than the bidding price. That means the buyers can buy power at a lower price than they intend to. Thus, the expense from trading at the average price is less than trading at the bidding price, causing the cost saving. With the equality of total revenue and cost saving, it creates economical balance [12]. The mathematical representation of this equation is given as follows:

$$\sum_{i=1}^{N} Revenue_i = \sum_{j=1}^{M} Cost\ saving_j \quad (4)$$

$$\begin{aligned} &\sum_j \left(P^{P2P}_{1,j} - a_1\right) q_{1,j} + \cdots + \sum_j \left(P^{P2P}_{N,j} - a_N\right) q_{N,j} = \\ &\sum_i \left(b_1 - P^{P2P}_{1,i}\right) q_{1,i} + \cdots + \sum_i \left(b_M - P^{P2P}_{M,j}\right) q_{M,i} \end{aligned} \quad (5)$$

where N and M are the number of sellers and buyers since i and j, respectively, and q is trading energy quantity in each pair.

Moreover, the clearing price of the traders who trade with the utility grid is the grid electricity rate. The grid electricity rate is defined as two rates: the maximum rate of the day and the minimum rate of the day. The seller sells power to the utility grid at the minimum rate of the day. On the other hand, the buyer purchases power from the utility grid at the maximum rate of the day. However, the grid electricity rate is used in P2P energy trading when the unbalance trading power in each pair occurs. In summary, the price in P2P energy trading can be divided into three cases based on the P2P trading power as follows:

- The total of the selling power equals the total of the buying power; all of the power is traded in the P2P network at the P2P price.
- The total of the selling power is less than the total of the buying power; some buyers will buy the rest from the utility grid at the maximum rate of the day.
- The total of the selling power is more than the total of the buying power; some sellers will sell the rest to the utility grid at the minimum rate of the day.
- The scenario process for the MO mechanism is formulated as shown in Algorithm 1.

There are two parts, which are the matching process and clearing price process. In the matching process, firstly, many orders, power and price, are sent to the MO in line 1. Then, the MO defines the P2P participant by price arranging in line 2–4. For P2P participants, the seller who offers the cheapest offering price is matched first. The matching process is based on the cost path. The distance factor is calculated in line 7 by (1) and the cost path is calculated in line 8 by (2). Thereby, the seller should be matched with the buyer who causes the least-cost path in line 9. With trading power, the case of trading can be divided into three cases. In the first case, in line 11–13, the supply equals the demand. Therefore, the total supply is sold to the buyer. In the second case, in line 14–16, the supply is less than the demand. Accordingly, the buyer is matched with another seller who has the rest of their power to trade based on the least-cost path. In the last case, in line 17–20, the supply is more than the demand. Thus, the seller has to match with another buyer who has the rest of their power to trade based on the least-cost path. Note that NaN means that the trader has already been matched and does not have enough power to trade. After matching, the P2P price will be calculated for the traders by the average mechanism in line 21.

Algorithm 1: Matching and Clearing Price mechanism

```
1:  Receive peer's order {power, price}
2:  Find P2P participants
3:  Bidding price arranging in descending order
4:  Offering price arranging in ascending order
5:  Start initial i = 1
6:  for i = 1: N
7:  Calculate DF
8:  Calculate CP
9:  Find jth buyer that causes the least CP
10: CP(j) = NaN
```

Algorithm 1: Cont.

```
if supply(i)–demand(j) = 0 then
break
end if
if supply(i)–demand(j) < 0 then
find ith seller based on the least CP
end if
if supply(i)–demand(j) > 0 then
find jth buyer that causes the least CP
CP(j) = NaN
end if
```
$P_{P2P} = \frac{1}{2}\left(a_i + b_j\right)$
```
end for
```

4. Proposed Re-Profiling Based BTF and Partitioning Zones in DSO Mechanism

In the DSO mechanism part, the DSO is responsible for checking the constraint which is the line congestion problem before trading. The traders cannot trade power if they violate this constraint. An increase of DERs will significantly increase the load in the distribution line. In addition, both sellers and buyers expect the payoff regardless of technical problems. These cause an over-limit network capacity. Therefore, the DSO must control the power in the line according to this constraint by decreasing the power in the line. The traders have to adjust their power profile based on the proposed congestion management approach. Hence, this section describes the use of BTF and the partitioning zone to remove a line congestion problem. BTF is used to define who has to adjust power and how much they should adjust because it reflects the correlation between the line power and bus power. Furthermore, the partitioning zone is used and it divides the area into two zones to manage trading power based on the management area.

4.1. Bus Transfer Factor (BTF)

BTF is defined as a response of power: how the power in the line will change if the generation power in the bus is adjusted. In depth, a high BTF is a high response of the power in the line to the change in the bus whereas a low BTF is a low response. That means each bus responds to the power in the congested line unequally. To decrease the power in the congested line, each bus's power should be adjusted based on this factor. It shows how much the power in the congested line (ΔF_l) changes when the power in each bus (ΔP_i) is adjusted. Hence, BTF is used to reflect the result of the response and to define who should participate in solving this problem. It is disputed using the following equation:

$$BTF_{l,i} \triangleq \frac{\Delta F_l}{\Delta P_i} = Y_{ft}\left(Z_{fi} - Z_{ti}\right) \quad (6)$$

where:

Y_{ft} is the element of the bus admittance matrix in row f and column t;
Z_{fi} is the element of the impedance matrix in row f and column i;
Z_{ti} is the element of the impedance matrix in row t and column i.

Note that f represents the beginning node of the considered line and t represents the final node of the considered line. Additionally, i is the bus whose power is adjusted. For the calculation example, Figure 3 presents a simple mesh network that includes three buses.

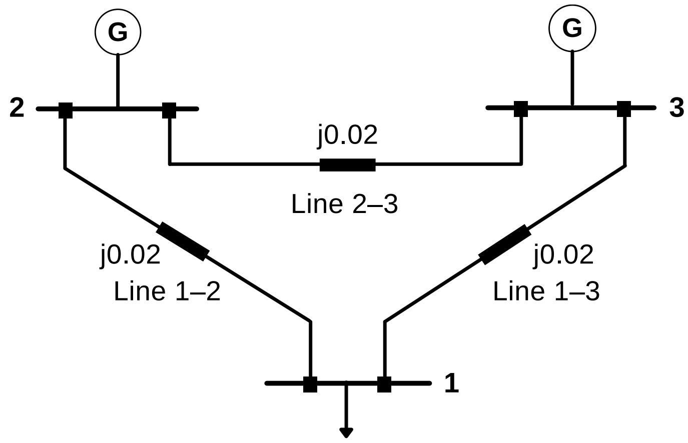

Figure 3. Example network for BTF calculation.

The bus admittance matrix is calculated. In this assumption, bus 1 is a slack bus; there is no change in the bus. The bus admittance matrix is shown as follows:

$$Y_{bus} = j\begin{bmatrix} -100 & 50 & 50 \\ 50 & -100 & 50 \\ 50 & 50 & -100 \end{bmatrix} \tag{7}$$

The slack bus is removed before calculating because it does not affect the process. The bus admittance matrix is resized as a 2 × 2 matrix. From the removal of the slack bus, the impedance matrix is shown as follows:

$$Z'_{bus} = j\begin{bmatrix} 0.0133 & 0.0067 \\ 0.0067 & 0.0133 \end{bmatrix} \tag{8}$$

The value of BTF from (6) is shown in Table 3. That means the change in bus 2 affects the change in line 1–2, 1–3, and 2–3, at −0.67, −0.33, and 0.33 times, respectively. For example, if the seller at bus 2 increases the selling power to 100 kW, this causes the power in line 2–3 to be increased by 33 kW. As well, the change in bus 3 affects the change in line 1–2, 1–3, and 2–3, at −0.33, −0.67, and −0.33 times, respectively. As a result, the different values are used to reflect the result of the change response. This factor is used together with the power adjustment.

Table 3. Calculating example of BTF.

Bus \ Line	1–2	1–3	2–3
2	−0.67	−0.33	0.33
3	−0.33	−0.67	−0.33

Because the change in the line power is not more than the change in the bus power, the value of BTF ranges from −1 to 1. As well, the sign shows the direction of the power flow. In specific circumstances, such as in a mesh network, it is possible for the power in the line to change unequally if the power in the bus changes. However, in a radial network, BTF is usually equal to −1, 0, and 1. The BTF value equals 1, which means that the amount of power in the line changes as equally as the amount of power in the bus. That is accurate because the power in the line flows in a single direction. If the value of the BTF is 0, it means that the change in the bus does not respond to the line. Those values indicate that the power adjustment in some buses may not be effective in removing the excessive power in congested lines. As well, each bus affects the congested line unequally, so the concept of BTF should be considered for line-congestion solving. We remark that the BTF can function with not only the function line component but also another network component such as the distribution transformer, if it can be described in the bus admittance matrix.

4.2. The Partitioning Zones

The partitioning zone is used to define how traders should adjust their power. In Figure 4, the power in the congested line flows from the left side to the right side. The total generation power is more than the total demand for the left side; the area on the left side of the dashed line is called the source area. On the other hand, the total demand is more than the total generation power for the right side; the area on the right side of the dashed line is called the load area. Moreover, the excessive generation power that dispatched from the source area to the load area is over the available capacity of the line, so it causes the congestion problem. To solve the problem, the concept of the partitioning zone is used to balance the power in each management area.

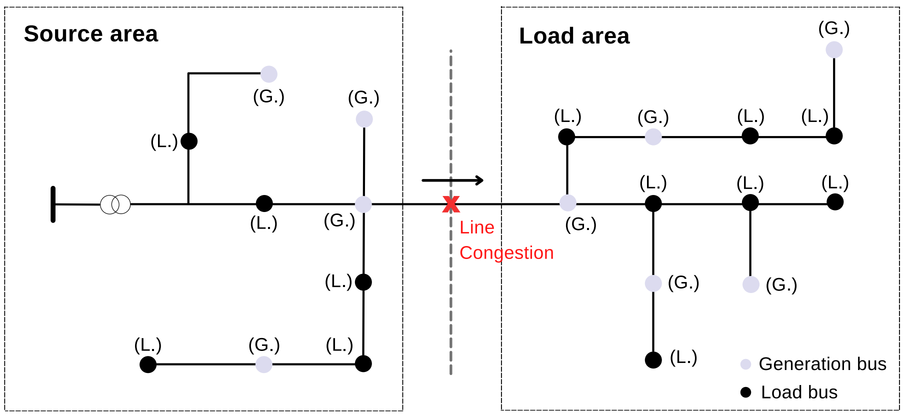

Figure 4. The partitioning zones.

In detail, the options for power adjustment in the source area include decreasing the generation power or increasing the demand. However, increasing the demand usage is not the appropriate way. The options for power adjustment in the load area include increasing the generation power or decreasing the demand. Possibly, decreasing demand will cut off the trading. Hence, for this work, sellers are defined as the main players for power adjustment in each area. Instead, if there are no sellers in the load area, buyers have to decrease their demand. With this proposed approach, the congestion problem is eliminated. As well, it creates more opportunities for buyers because there is no need to decrease their demand immediately when a line congestion problem occurs.

Equation (9) is used to calculate how much traders have to adjust the total bus power for the removal of the excessive power in the congestion line. It relates to the change in the line power when the power injection at the bus changes. With the equation, decreasing power in the source area (10) would be compensated by increasing power in load area (11), based on the previous generation power ratio in each area and BTF value. The factor represents the response between the change in power on the buses and the change in power on the congested line. Therefore, the mathematical equations of the power adjustment are calculated as follows:

$$F_l = F_l^0 + \sum_{i \in sa} P_{i,dec} + \sum_{i \in la} P_{i,inc} \tag{9}$$

$$P_{i,dec} = BTF_{l,i} \frac{P_i}{\sum_{n \in sa} P_n} (-\Delta P_i) \tag{10}$$

$$P_{i,inc} = BTF_{l,i} \frac{P_i}{\sum_{n \in la} P_n} (\Delta P_i) \tag{11}$$

where:

$BTF_{l,I}$ is the change in line l as ΔF_l when compared to the change in bus i as ΔP_i;

F_l is the maximum power flow of the line;
$F_l{}^0$ is the power flow in the line before solving the congestion problem;
$P_{i,dec}$ is the decreased power in the source area;
$P_{i,inc}$ is the increased power in the load area;
ΔP_i is the excessive power in the congested line.

In the same way, if the buyers in a load area have to decrease their demand instead, the mathematical representation of this power adjustment equation is the same as (10) in the terms of the load area.

The constraint management algorithm from the DSO mechanism is presented in Algorithm 2. After the sellers and buyers finished the matching and clearing price process, the MO sends the DSO the total power profiles to check which line has a congestion problem shown in line 1–2. The trading occurs when the power in the line is under the capacity limit. If a congestion problem occurs, sellers have to adjust their generation power based on the BTF and the management area in line 5–6. If the line is not congested, the DSO will allow the dispatch of power and the MO can send the participants the settlement bill in line 7–9.

Algorithm 2: Congestion management

1: Receive total power profile
2: Check for a congestion problem
3: $BTF_{l,i}$ is calculated
4: if a congestion problem is true then
5: Adjust power based on BTF.
Each seller in gen. bus at source area decreases power as $P_{i,dec}$
6: Each seller in gen. bus at load area increases power as $P_{i,inc}$
7: if a congestion problem is false then
8: settlement and dispatch
9: end if

5. Compensation for Congestion Management

When the participants changed the power profile for the line congestion solution, they deserve a compensation from the MO. The compensation will persuade the participants to be willing to adjust their power. It should reflect the amount of the power adjustment. Nevertheless, in some cases, the participants adjust less power, so a compensation based on the power adjustment is less. With this reason, they may not be willing to adjust their power profiles. To induce them, a fixed compensation rate should be included in the compensation as well. Hence, the total compensation (TC) that includes the fixed rate (R_f) and the adjustable rate (R_a) is calculated as follows:

$$TC = R_f + R_a \tag{12}$$

The fixed compensation rate is a standard rate to compensate immediately the participants who participated in congestion management. It is fixed, regardless of the amount of the adjusted power. The participants who participate in solving this problem receive the fixed rate equally. The interruptible service rate based on the incentive rate of the demand response is applied to the fixed rate. It differs in different markets, provided that the compensation does not cause profits instead of trading.

The adjustable rate is a compensation rate based on the power adjustment, which comes from different additional expenses that participants pay for buying power from the grid. In a network, power from the utility grid is injected to both P2P loads and normal loads. If the total P2P selling power is not equal to the total P2P buying power, traders will get the rest of their power from the utility grid. Normal loads, not involved in P2P energy trading, have to be traded with the utility grid. Therefore, some expense occurs between the utility grid and load within the network. After solving the congestion problem by the proposed approach, the increased selling power in the load area is refuted with the decreased selling power in the source area. That means the power quantity flowing from the utility grid does not have any change. However, for congestion management in a radial network, there are only sellers or buyers in the load area who are able to adjust their power. Hence, power increasing or demand decreasing causes the load quantity within the network to be lower. That means it is refuted by a reduction in the power from the utility grid instead. The lower load quantity is equal to the excessive power in the congested line. The total power from grid decreases, causing there to be less money flowing out from the network to the utility grid. The difference in money is called virtual profit (*VP*). It is disputed as follows:

$$VP = (R_{max})\left(P_0^{G2P} - P_1^{G2P}\right) \tag{13}$$

where:

R_{max} is the maximum rate of the day;

${P_0}^{G2N}$ is the power from the utility grid to the network before congestion solution;

${P_1}^{G2N}$ is the power from the utility grid to the network after congestion solution.

The *VP* after deducting the congestion cost (*CC*) is an adjustable rate in (14). It is distributed to the participants who involved in solving the congestion problem. The adjustable rate of each participant is based on the power adjustment proportion.

$$R_a = VP - CC \tag{14}$$

The *CC* calculation method for the deregulated market in [33] is applied in this work. It is the unit price of the difference in power that causes a congestion and un-congestion problem. The difference in power refers to the adjusted power. Therefore, the total *CC* is calculated from the cost of the first participant to the last participant who participates in the congestion solution as follows:

$$CC = \sum\nolimits_i^N (a_i)\left(P_{adj,i}\right) + \sum\nolimits_j^M (b_j)\left(P_{adj,j}\right) \tag{15}$$

where *N* and *M* are the number of sellers and buyers since *i* and *j*, respectively, and P_{adj} represents the adjusted power as increased power or decreased power.

6. Case Studies and Discussion

This section explains two cases, a study of the matching process and a study of congestion management and compensation. The first case study focuses on the matching process with the cost path consideration and the clearing price process. The congestion problem does not occur in this case. Hence, the DSO allows the traders to trade power with each other.

The second case study presents the congestion solution with the BTF and the partitioning zone as well as compensation. This case compares the opportunity cost between this proposed congestion management and demand-side reprofiling approach (DSRM). The DSRM is a power adjustment by decreasing the load immediately when a congestion problem occurs. It is decreased by following the power adjustment proportion. Moreover, the settlement bill for the total transaction is presented in both cases.

To validate the proposed approach, the IEEE 13 node test feeder is used and modified. Depending on the net power in each bus, the thirteen buses could either be generation buses or load buses. The first bus is defined as a slack bus. In this assumption, the ten trading participants can switch roles between sellers and buyers in each trading period. To comply with the actual trading in the electricity market, normal loads which do not involve in P2P energy trading are defined in some buses. The bid is randomized between the minimum rate of 0.06 USD/kWh and the maximum rate of 0.17 USD/kWh.

6.1. Case 1: A Study of Matching Process

For a study of the matching process, the congestion problem is not considered. The test feeder is modified in Figure 5. There are five sellers, i.e., C, D, E, F, and I, and five buyers, i.e., A, B, G, H, and J. The power quantity, price, and line length are shown in Figure 6. The line length represents the distance between nodes.

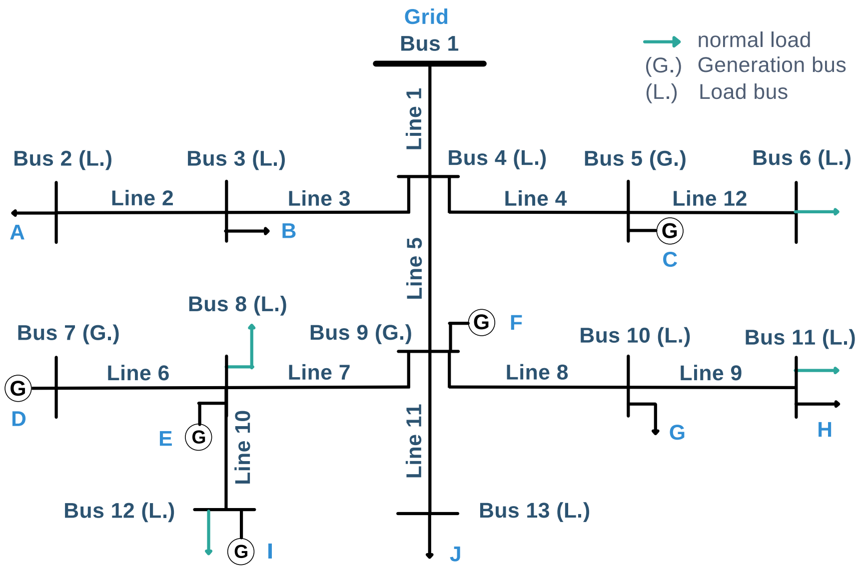

Figure 5. Modified IEEE 13 node test feeder for Case 1.

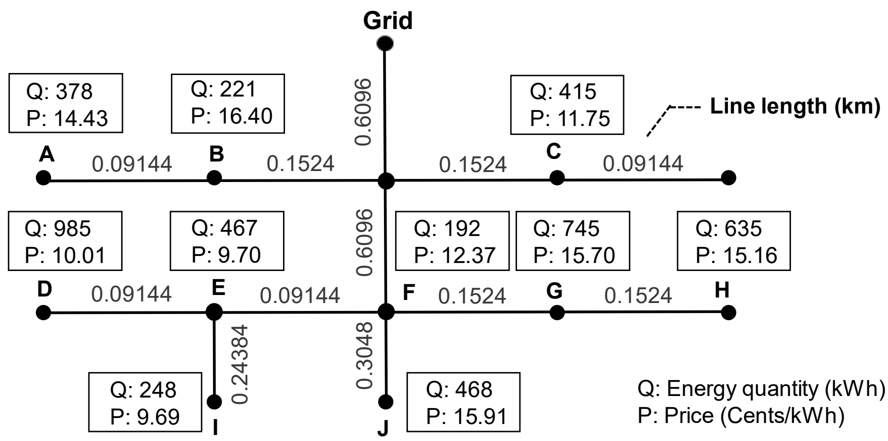

Figure 6. Information of power quantity, price, and distance between nodes for Case 1.

According to the result of the price sorting, all traders can participate in P2P energy trading. By sorting the seller's offering price in ascending order, the priority of the P2P sellers is seller I, E, D, C, and F, respectively. In the MO mechanism, the operator finds the trading pair for seller I, first. The shortest distance from seller I to buyers A, B, G, H, and J are 1188.72 m, 1097.28, 487.68, 640.08, and 640.08 m, respectively. Thereby, the total shortest distance is 4053.84 m, and the distance factor is then calculated. Likewise, for other sellers, the least possible distance is considered. Therefore, the distance factor of all sellers is shown in Table 4. To calculate the cost path, the bidding price of the buyers is multiplied by the factor because the dispatch occurs for the buyers' demand response, described in Section 3. The cost path is shown in Table 5. For example, the distance factor between seller I and buyer A is calculated from the shortest distance of 1188.72 m divided by the total shortest distance of 4053.84 m. Hence, the distance factor is 0.2932. By multiplying with the bidding price of buyer A, the cost path is 0.0423 USD/kWh. It is the same calculation for the others.

Table 4. The distance factor.

Seller \ Buyer	**A**	**B**	**G**	**H**	**J**
I	0.2932	0.2707	0.1203	0.1579	0.1579
E	0.3333	0.3011	0.0860	0.1398	0.1398
D	0.3148	0.2870	0.1019	0.1481	0.1481
C	0.1057	0.0813	0.2439	0.2846	0.2846
F	0.3590	0.3205	0.0641	0.1282	0.1282

Table 5. The cost path in USD/kWh.

Seller \ Buyer	**A**	**B**	**G**	**H**	**J**
I	0.0423	0.0444	0.0189	0.0239	0.0251
E	0.0481	0.0494	0.0135	0.0212	0.0222
D	0.0454	0.0471	0.0160	0.0225	0.0236
C	0.0152	0.0133	0.0383	0.0431	0.0453
F	0.0518	0.0526	0.0101	0.0194	0.0204

With this proposed matching approach, the traders should be matched with two conditions, the least-cost path and the priority of sellers, as shown in Table 6. From considering Table 5 and Figure 6, the trading pair and the matching order are described as follows:

- In the first step, considered the first row, seller I matches with buyer G. Nonetheless, the information of the power quantity in Figure 6 shows that the supply is less than the demand. Thereby, all the supply of seller I is sold to buyer G and buyer G has to buy the rest of their demand from another seller based on the least-cost path.
- Considering the third column, buyer G matches with seller F and seller E with the demand of 192 kWh and 305 kWh, respectively. Hence, buyer G has already bought their total electricity.
- Nevertheless, seller E has the rest of their supply to sell; the row of seller E is considered. Seller E sells the rest of their power to buyer H with a power supply of 162 kWh. Definitely, this is less than the demand of buyer H.
- From the least-cost path in the column of buyer H, buyer H should be matched with seller F but the supply of seller F is sold out. Therefore, buyer H is matched with seller D with the demand of 473 kWh and buyer H has already bought the total electricity.
- Next, the row of seller D is considered. Seller D has the rest of their supply to sell, so it is sold to buyer J and buyer A, respectively. Hence, buyer J has already bought the total electricity but buyer A has to buy the rest of their demand from another seller.
- Considering the first column, buyer A has to buy the rest from seller C with the demand of 334 kWh.
- Next, the row of seller C is considered. Seller C sells the rest to buyer B with the supply of 81 kWh. Hence, seller C has already sold their total electricity, but buyer B has to buy the rest of their demand from another seller.
- However, the total supply of all sellers is less than the total demand of all buyers. As well, all sellers have already sold their supply. Thereby, buyer B has to buy the rest of their demand from the utility grid with the demand of 140 kWh.

Table 6. Results of transaction: trading energy part.

Trading Energy (kWh)						
Seller \ Buyer	**A**	**B**	**G**	**H**	**J**	**Grid**
C	334	81	-	-	-	-
D	44	-	-	473	468	-
E	-	-	305	162	-	-
F	-	-	192	-	-	-
I	-	-	248	-	-	-
Grid	-	140	-	-	-	-

In each trading matching, the P2P price is calculated by the average mechanism. It is calculated from the offering price of the seller and the bidding price of the buyer. For example, with the first trading pair between seller I and buyer G, the P2P price is calculated from the offering price of 0.10 USD/kWh and the bidding price of 0.16 USD/kWh. Hence, the P2P price equals 0.13 USD/kWh. With the trading energy of 248 kWh, the settlement bill is 31.47 USD. For other transactions, the settlement bill is shown in Table 7.

Table 7. The settlement bill.

Settlement Bill (USD)						
Seller \ Buyer	**A**	**B**	**G**	**H**	**J**	**Grid**
C	43.72	11.40	-	-	-	-
D	5.38	-	-	59.53	60.67	-
E	-	-	38.73	20.14	-	-
F	-	-	26.95	-	-	-
I	-	-	31.47	-	-	-
Grid	-	23.20	-	-	-	-

When the transaction process has finished, the traders are matched by both appropriate distance and price. From the settlement bill in each pair, it shows that the sellers can sell electricity at a higher price and the buyers can buy electricity at a lower price. However, the congestion problem does not occur in this case. Therefore, the sellers and buyers can exchange their power immediately. To show how the DSO manages the congestion problem, the next case study presents the process.

6.2. Case 2: A Study of Congestion Management, the Compensation, and the Opportunity Cost

For a study of this case, it is described in three parts: the proposed congestion management, compensation, and comparison of the opportunity cost between this proposed approach and the DSRM. To highlight this case, a congestion problem occurs so the DSO has to manage this problem for the traders to be able to trade power. Definitely, the power profile of traders will be re-profiled after solving this problem.

6.2.1. Congestion Management Based on BTF and Partitioning Zone Method

In this case, there are six sellers, i.e., A, B, C, D, F, and J, and four buyers, i.e., E, G, H, and I. The test feeder is modified. The power quantity, price, and distance between nodes are shown in Figure 7. From the result of the price sorting in the step function, there are seller A, C, D, and F and buyer E, G, H, and I who can participate in P2P energy trading, so participants B and J have to trade with the utility grid. By sorting the offering price of the sellers in ascending order, the priority of the P2P sellers is seller F, A, C, and D, respectively. In the MO mechanism, the operator finds the trading pair and defines the P2P price for the P2P participants. This is in accordance with the cost path and average mechanism. The matching process is the same as in Case 1. According to the result of the transaction, the trading energy is shown in Table 8.

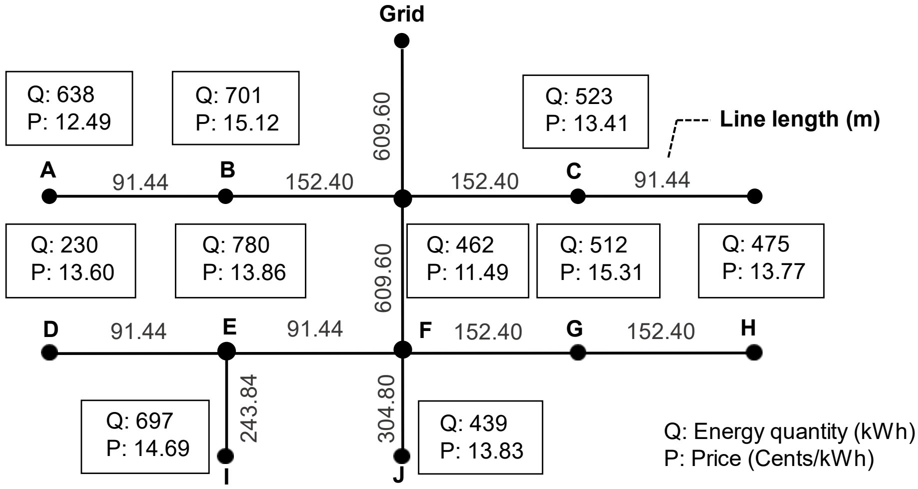

Figure 7. Information of power quantity, price, and distance between nodes for Case 2.

Table 8. Results of transaction: trading energy part after matching process.

	Trading Energy (kWh)				
Seller \ Buyer	**E**	**G**	**H**	**I**	**Grid**
A	-	77	475	86	-
B	-	-	-	-	701
C	88	435	-	-	-
D	230	-	-	-	-
F	462	-	-	-	-
J	-	-	-	-	439
Grid	-	-	-	611	-

With energy trading in Table 8, the DSO checks the congestion problem. The line congestion problem occurs in Line 5 and Line 7. Firstly, Line 5 is solved because the excessive power over the line limit is more than another line. The power in Line 5 is over the limit at 1373.91 kW. Hence, the total power adjustment equals the value to decrease the power in the congested line. In the DSO mechanism, the operator divided Line 5 into two sides based on the direction power of the line as shown in Figure 8. Power flows from top to bottom, so the source area is above the dashed line and the load area is under the dashed line. The sellers are the main players for the power adjustment; therefore, the sellers in the source area are seller A, B, and C. They have to decrease their generation power as well. The sellers in the load area are seller D, F, and J. They also have to increase their generation power. By balancing the power in each management area, the congestion problem in Line 5 is solved.

The BTF is considered to define how much they increase or decrease power. The BTF, the result of the change response between the line power and the bus power, is calculated and the values are shown in Table 9. According to the BTF of the radial network described in Section 4, the BTF values are 0 and -1. The BTF values show that the sellers in the source area do not participate in a congestion solution because those values are 0. Thereby, there are only sellers in the load area participating in the congestion solution; they have to increase their generation power. That means the increased P2P power is refuted by a reduction in the power from the utility grid. To comply with the generation power capacity, this work assumes that sellers can increase the generation power which is equal to 30 percent of the generation power based on the upper generation limit. According to (9), seller D, F, and J increase the generation power at 279.40, 561.22, and 533.28 kW, respectively. Yet, it is over the capacity limit of each seller; the sellers can increase the generation power which is equal to the maximum capacity limit.

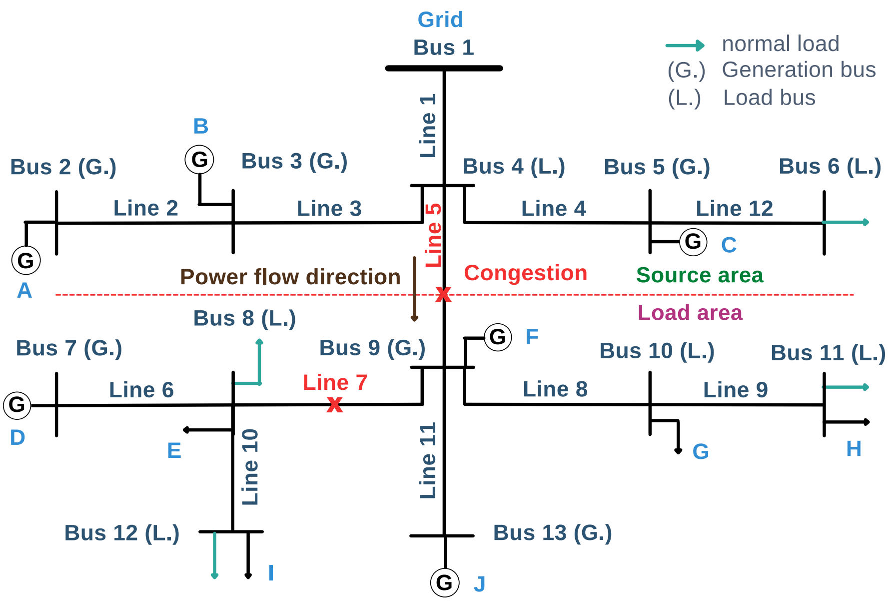

Figure 8. The partitioning zones for Case 2.

Table 9. BTF value.

Bus \ Line	5	Bus \ Line	5	Bus \ Line	5
Ref. bus	-	7	−1	13	−1
2	0	8	−1		
3	0	9	−1		
4	0	10	−1		
5	0	11	−1		
6	0	12	−1		

When the DSO considers the upper generation limit, the total increased power by the sellers in the load area is less than the total required adjusted power. Therefore, the buyers in the load area need to decrease their load based on the power proportion to remove the line congestion problem as well. To conclude, seller D, F, and J increase their generation power whereas buyer E, G, H, and I decrease their demand. The total power adjustment of each participant is shown in Table 10. To compare with the DSRM [34], the decreased load by the approach is shown in Table 10 as well. In the DSRM, when a congestion problem occurs, the DSO forces the buyers to immediately decrease their demand, based on the power proportion. It is different from this proposed approach. In the proposed approach, the sellers are first managed. They increase the generation power as much as possible before the buyers decrease their load. According to the approach, the traders have more opportunity to trade their power.

Table 10. Power adjustment based on the proposed method and DSRM.

Participant	DSRM (kW)	Proposed Method (kW)
seller D	-	69.00
seller F	-	138.60
seller J	-	131.70
buyer E	−434.92	−327.51
buyer G	−285.49	−214.98
buyer H	−264.86	−199.45
buyer I	−388.64	−292.66

After the solution, the power of the traders is re-profiled. The new generation power of the sellers is increased whereas the new demand of the buyers is decreased. For the new generation power, seller D, F, and J sell power at 299.00, 600.60, and 570.70 kW, respectively. For the new demand, buyer E, G, H, and I buy power at 452.49, 297.02, 275.55, and 404.34 kW, respectively. However, the power of other traders does not have any change. It is the same value before solving this congestion problem because they do not adjust power for this congestion solution. They are then re-matched, which is based on the proposed matching approach by the MO. The trading energy after re-profiling is shown in Table 11. Moreover, the settlement bill is shown in Table 12 which is calculated from the P2P price and the new adjusted power profile. After solving the congestion problem in Line 5, the congestion problem in Line 7 is cleared as well.

Table 11. Results of transaction: trading energy part after re-profiling.

	Trading Energy (kWh)				
Seller \ Buyer	E	G	H	I	Grid
A	-	-	-	6.80	631.20
B	-	-	-	-	701.00
C	-	148.91	275.55	98.54	-
D	-	-	-	299.00	-
F	452.49	148.11	-	-	-
J	-	-	-	-	570.70
Grid	-	-	-	-	-

Table 12. The settlement bill after re-profiling.

	Settlement Bill (USD)				
Seller \ Buyer	E	G	H	I	Grid
A	-	-	-	0.92	39.68
B	-	-	-	-	44.06
C	-	21.39	37.45	13.84	-
D	-	-	-	42.28	-
F	57.34	19.85	-	-	-
J	-	-	-	-	35.87
Grid	-	-	-	-	-

6.2.2. The Compensation for Power Adjustment

The next step is a compensation. The compensation is divided into two parts, consisting of the fixed rate and adjustable rate. In accordance with the interruptible service rate, the fixed compensation rate for this model is assumed to be 5 USD. It is distributed to the participants who participate in a congestion solution equally. Moreover, the adjustable rate based on the power adjustment proportion is distributed after deducting the congestion management cost. The virtual profit in (13) is 233.56 USD. The total congestion cost in (15) is 192.29 USD; therefore, the total adjustable compensation rate is 41.27 USD. Moreover, the adjusted power proportion of participants D, F, J, E, G, H, and I are 0.05, 0.10, 0.10, 0.24, 0.16, 0.15, and 0.21, respectively. For example, the power proportion of seller D is calculated from the increased power of 69.00 kW divided by the total adjusted power of 1373.91 kW. It is the same process for other participants. Hence, the compensation rate for the power adjustment equals the values as shown in Table 13.

Table 13. The compensation rate for power adjustment.

Participant	Fixed Rate (USD)	Adjustable Rate (USD)	Sum (USD)
seller D	5	2.06	7.06
seller F	5	4.13	9.13
seller J	5	4.13	9.13
buyer E	5	9.90	14.90
buyer G	5	6.60	11.60
buyer H	5	6.19	11.19
buyer I	5	8.67	13.67

6.2.3. Comparison of Opportunity Cost between the Proposed Approach and DSRM

As in the above result, this work discusses the opportunity cost between this proposed congestion solution and the DSRM as shown in Figure 9. For the DSRM, buyers need to decrease their demand immediately, which leads them to trade less power. This causes damage because buyers lose more chances to purchase electricity for use in their house or doing their business. The more the load is decreased, the higher the damage is. Nonetheless, for this proposed congestion solution, the load reduction step is after the generation power increasing step. Moreover, in most cases, buyers do not need to decrease their load if the congestion problem is already cleared by the increase of the generation power. Thereby, the demand of the buyers is less cut off, which leads them to be able to buy more power for their businesses.

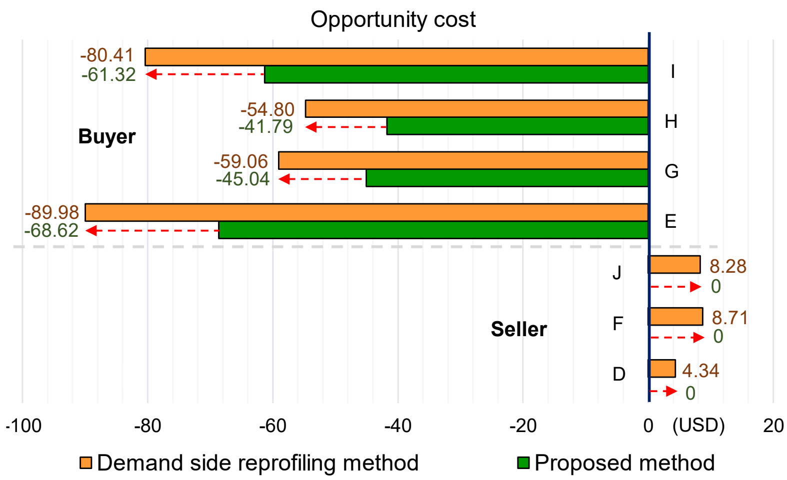

Figure 9. Comparison of the opportunity cost between the proposed approach and DSRM.

To present in terms of numerical data, this work will be described in two parts, consisting of the opportunity cost of the sellers and opportunity cost of the buyers. It is the highest alternative value that is not chosen. Firstly, with this proposed approach, sellers get more chances to sell their power by 30% because of the increase of the generation power. With the DSRM in Table 10, seller D, F, and J lose a chance to sell more power at 69.00 kW, 138.60 kW, and 131.70 kW, respectively. Hence, the total opportunity cost of the sellers is 21.33 USD. The unit price for calculating a return for the sellers is the minimum price rate of the day. In Figure 9, for example, if the congestion solution is the DSRM, the opportunity cost of seller D is 4.34 USD because the seller loses a chance to sell more power of 69.00 kW.

Secondly, buyers need to decrease the total power at 1373.91 kW for the DSRM. However, with this proposed approach, they decrease the total power at 1034.61 kW. Therefore, they get more chance to buy power by 24.70%. In this assumption, buyers can generate a return of 1.2 times of the electricity expense. In fact, the bigger the business is, the more the damage from the reducing load is. The unit price for calculating a return for the buyers is the maximum price rate of the day. Therefore, the total opportunity cost of the buyers is 216.77 USD for the proposed approach. For the DSRM, the total opportunity cost of the buyers is 284.25 USD. In Figure 9, for example, if the congestion solution is the DSRM, buyer E has to decrease the demand of 434.92 kW as shown in Table 10. As a result, buyer E purchases the net demand of 345.08 kW. It is calculated as a return which is equal to 68.62 USD. Nevertheless, for the proposed approach, the buyer has to decrease the demand of 327.51 kW, so he buys the net demand of 452.49 kW. It is calculated as a return which is equal to 89.98 USD. Hence, the opportunity cost of buyer E is the value for the DSRM.

From the comparison, it shows that the opportunity cost of the traders for the proposed approach is less than the opportunity cost for the DSRM. Thereby, it is better to remove the congestion problem according to the proposed approach because it creates more chances for the sellers and creates less damage for the buyers. As well, the participants receive a compensation.

7. Conclusions

This work proposed a matching approach, based on cost path, and a congestion solution, based on the BTF and partitioning zone approach, for P2P electrical energy trading. The operator is required to consider the overall market for effective energy trading. The trading processes consist of the MO and DSO mechanism. In the MO mechanism, traders are matched based on the least-cost path. This represents the trading cost in each route. In the DSO mechanism, the DSO checks the congestion problem in the distribution line before permitting the trading. The proposed line congestion management process occurs after the market clears, so the traders can trade liberally, initially.

To approve the proposed mechanisms, the first case study focuses on a matching process. The traders are matched based on the least-cost path considering the distance and the bids. From the result of the matching process, the farther traders are not obstructed from trading. Most works which consider only the distance condition focus on trading with a closest trader. This obstructs trading with the farther traders and contrasts with the liberated energy trading context. Moreover, the return will be diminished possibly if the bids are not regarded because both the distance and the bids are all factors affecting the return. Thus, it is better to consider the distance together with the bids.

In the second case study, the focus is on the congestion management. The MO pays a compensation to the traders to induce them to be willing to adjust their power. The power adjustment is based on the proposed BTF characteristic, that reflects a power change in each bus compared to a power change in the congested line, and partitioning concept. From the result of this case, the proposed approach can remove the congestion problem under the available capacity of line. In detail, a change in the power of the seller in the source area does not affect the solution. Hence, sellers in the area do not participate in solving the congestion problem because the power flows in a single way in a radial network. That shows the traders in each bus do not need to adjust the amount of power equally to remove the excessive power in the congested line because the response to the power in the line is unequal. Moreover, with the discussion about the opportunity cost in this case, the proposed congestion management is more appropriate than DSRM because the seller is a key player for power adjustment in the proposed approach. Normally, a way to remove the excessive power in the congested line is load and generation power curtailing immediately. With the DSRM approach, buyers lose a chance to buy their total demand by 24.70% and sellers lose a chance to sell power by 30%. This causes damage to both the buyers and sellers. By this proposed approach, it causes less damage for the buyers and creates a chance for the sellers to increase the generation power as much as possible to trade more electricity.

For the direction of future works, it is possible to implement P2P energy trading in a mesh network that is different from the radial network. This requires additional considerations such as multidirectional dispatch, zone designation, and the amount of loop. Thereby, this approach should be proven for the mesh network in the future.

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