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Analyzing Various Aspects of Network Losses in Peer-to-Peer Electricity Trading

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Abstract: In this study, we examined the impacts of peer-to-peer (P2P) electricity trading on the power losses in the network, which is one of the objectives optimized in the centralized approach. For this purpose, we reviewed the conventional loss management schemes and suggested the requirements to be considered in the design of P2P electricity trading. Then, we described a new loss management framework for P2P transactions and introduced the concept of the transaction guide. Based on the proposed framework, we simulated the P2P transactions with and without the transaction guide and examined the variation in the network losses. Three noteworthy remarks are derived from the simulation in this paper. First, the random characteristics of P2P trading itself do not guarantee favorable transaction ordering in terms of network losses, but when the new loss management framework is applied, the network losses can be effectively decreased. Second, through the new loss management framework, loss costs can be fairly allocated to individual prosumers. Third, to invigorate the P2P electricity trading, an incentive program should be considered to alleviate the burden of loss costs of the first trader in the P2P electricity trading.

Keywords: peer-to-peer (P2P) electricity trading; loss management; transaction guide; electricity market

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1. Introduction

Growing concerns about climate change and environmental problems have made "Decarbonization" an essential issue in the electricity sector [1]. In this regard, renewable energy sources (RES) are receiving a great deal of attention [2,3]. Further, the number of dispersed RES of small size continues to grow, thereby decentralized power systems for facilitating the use of distributed energy resources (DERs), including not only small RES but also energy storage systems and controllable loads, are the concerns of importance.

In conventional power systems, power and energy have mainly been generated from fossil fuel generators located far from load centers and connected to high voltage transmission networks. However, DERs in decentralized power systems are usually connected to low/medium voltage grids close to loads [4]. Therefore, the network efficiency of the conventional power systems in terms of, e.g., transmission losses, can be improved when the utilization of DERs in the decentralized power systems increases. Further, with advanced measurement infrastructure (AMI) and information and communications technologies (ICTs), DERs in decentralized power systems can contribute to the balance of generation and consumption in near real-time in the local grid [4,5]. Additionally, decentralized power systems can maximize the energy utilization of users in the network and facilitate the penetration of additional renewable sources. Therefore, decentralized power systems can be regarded as "carbon positive" not only because DERs are usually close to carbon-neutral but also because they have merits in the flexible and efficient use of electricity.

As one of the ways to take advantage of this flexibility and efficiency of decentralized power systems, peer-to-peer (P2P) electricity trading where passive consumers become active prosumers (producer + consumer) is regarded as a promising alternative [6,7]. Some electricity companies have already introduced P2P electricity trading projects in distribution networks [3]. In the USA, energy prosumers in the Brooklyn Microgrid platform trade electricity using blockchain [4]. In the United Kingdom, the Piclo platform matches energy prosumers every half hour using a matching algorithm that considers each prosumers' location and preferences [8]. However, most P2P electricity trading projects are at the beginning stage, and still, there are challenges to be addressed to enjoy the advantages of P2P electricity trading fully. It is because electricity exchange is different from other exchanges of goods, and prosumers are parts of a physical electricity network subject to technical constraints and security requirements [6,8]. Coordinating the conflicting objectives of prosumers and encouraging them to act in a trustworthy way are also essential matters in P2P electricity trading where a central controller does not influence a lot on the decision of participants [6,8].

For these reasons, many studies have aimed to propose a better way of P2P electricity trading. In [7,9–11], methodologies of allowing only peer-matches that do not violate network constraints, such as voltage rules and line congestion, are presented. The studies in [12–15] focused on the transaction mechanism that can maximize social welfare, and those in [16–20] suggested methods for fairly allocating network fees to users. Some studies examine adopting new technologies in P2P trading mechanisms. In [21–23], blockchain technology and smart contract are introduced as tools for trading and settlement between untrustworthy producers and consumers. Among the points of interest related to P2P electricity trading, this study focuses on the power losses in the network, which are important features that are directly related to the utility of P2P electricity trading. The increase of power losses in the grid can raise the network utilization costs in the local network and thus, can weaken the merits of P2P electricity trading.

In conventional power systems, the power losses in the grid were managed by the network operator mainly in three ways: pro-rata procedures, proportional sharing procedures, and marginal procedures [24–35]. In pro-rata procedures and proportional sharing procedures, a network operator coordinates transactions considering the market needs, such as loss minimization or profit maximization, and proceeds dispatch. After that, the network operator calculates the total loss cost during the settlement process and allocates it to the grid users based on specific rules, for example, proportional allocation rules or power flow tracing methods [24–33]. In marginal procedures, a network operator calculates and allocates the loss costs through so-called incremental loss coefficients during the dispatching procedure based on the optimal power flow (OPF) method [24,25,34,35].

However, these conventional loss management methodologies are somewhat inconsistent with P2P electricity trading in two ways. First, conventional methodologies request the network operator to play a central role in calculating, minimizing, and allocating the loss costs while coordinating transactions and managing the network [24–35]. Second, they are suitable for call markets, that is, the basic structure of many conventional electricity markets, where all bids and offers submitted are cleared at a scheduled time. In contrast, the role of intermediary third party is minimized when peer-matches are established in the P2P trading through, e.g., continuous double auction (CDA) mechanism. Considering the characteristics of the P2P electricity trading, some studies suggested an electricity market based on CDA mechanism [36–40]. In [13,36,37], CDA market structure and methods of preventing transactions that violate network constraints are suggested. In [38], blockchain technology was adopted to minimize the influence of operators in the electricity network. Studies in [39,40] examined the P2P electricity market from prosumers' perspectives. An automated negotiation framework was suggested [39], and prosumers' welfare in attending the P2P electricity market was analyzed [40]. However, it is hard to find the previous literature that focused on the loss management method in the CDA based P2P electricity market.

In this context, this study examines a new loss management methodology that reflects the decentralized characteristics of P2P electricity trading. In the new methodology, the network operator does not put much effort into calculating, minimizing, and allocating the loss costs by itself. Instead, it guides the network users to find and trade electricity with the counterparty causing smaller power losses in the network. The transaction guide needs to consider not only the electrical distance between peers but also the continuously changing power losses as transactions are completed one by one. However, will the new methodology be effective enough in minimizing losses compared to the conventional methods? What will be the best form of the new methodology that can maximize its benefit of reduced losses? What should be considered in designing the new methodology for fairly assigning the losses while ensuring the active participation of users in P2P trading?

Answering the questions will be the remainder of this paper. In Section 2, after reviewing the conventional loss management schemes, the reason why the new loss management scheme is needed in P2P trading is discussed. After that, in Section 3, we discuss the new loss management scheme suitable for P2P trading. To check the effectiveness of the new loss management scheme, we set up the simulation in Sections 4 and 5. Then, after the simulation, we examine and discuss the results in Section 6. Finally, concluding remarks are provided in Section 7.

The contributions of this paper can be summarized as follows:

- The new loss management methodology based on CDA mechanism considering the characteristics of P2P electricity trading is suggested;
- The new loss management methodology, which adjusts prosumers' bids and offers in the order book considering the network impacts, effectively guides prosumers to trade electricity in the loss minimizing way;
- The new loss management methodology can fairly allocate loss costs to prosumers;
- Needs of the incentive program for the first trader to invigorate the P2P electricity trading are discussed.

2. Issues about Losses in Power Systems

2.1. Difficulties of Managing Losses

Managing Losses has always been an essential issue in the power system. Loss in the power system prevents the efficient use of energy and causes an increase in carbon emissions. It also breaks the planned supply and demand and causes difficulties in network operation. Some generators may have to generate more to make up for the deficit of power in the network, and this leads to the problem of "who should pay for losses," i.e., the matter of allocating the costs of losses.

For example, in one situation, a transaction between network users can increase losses in the network. However, in the other situation, the same transaction can diminish losses by inducing reverse power flow in the network. Further, the power flow in the network is affected by the physical conditions of the system. In other words, some network users may claim that they are at a disadvantage in terms of loss allocation when they keep taking too much burden on the loss costs.

Due to this complexity, in conventional power systems, the matter of losses has usually been handled by network operators with high accessibility to information on the electricity market and network. The methods that network operators use can be divided mainly into the embedded cost allocation method and the marginal procedure. In the electricity market, using the embedded cost allocation method, a network operator focuses on calculating the overall network management costs, including loss costs, and allocating it to network users after delivery through the pro-rata procedure (Section 2.2.1) or proportional sharing procedure (Section 2.2.3). In the power market based on the marginal procedure (Section 2.2.2), a network operator reflects the liability for losses in each transaction before the delivery of electricity by using the optimal power flow method.

2.2. Conventional Loss Management Schemes

2.2.1. Pro-Rata Procedure

In the pro-rata procedure, the most straightforward loss management schemes, total losses are assigned to groups of generators and loads, 50% each [24,25,30]. Then, losses allocated in each group are divided based on the active power generation and active power demand of each group member [24,25,30]. That is,

$$L_{G_i} = \frac{L}{2}\frac{P_{G_i}}{P_G} = K_G P_{G_i}, \quad L_{D_j} = \frac{L}{2}\frac{P_{D_j}}{P_D} = K_D P_{D_j} \tag{1}$$

where L are the total losses to be allocated to generators and loads, L_{G_i} are the losses allocated to generator i, L_{D_j} are the losses allocated to the demand j, K_G is the generation loss allocation factor, and K_D is the demand loss allocation factor. Generation loss allocation factor K_G is identical for all buses [24]. Likewise, demand loss allocation factors K_D is also identical for all buses [24].

2.2.2. Marginal Procedure

In the marginal procedure, losses are allocated to generators and demands using the incremental transmission loss (ITL) coefficients [24,25,34,35]. ITL coefficients K_{ITL_i} is defined as a change in total losses L_{total} attracted by an incremental change in the power injected in the bus I [24,25,34,35].

$$K_{ITL_i} = \frac{\partial L_{total}}{\partial (P_{G_i} - P_{D_i})} \tag{2}$$

Using the ITL coefficients, changes in the losses by the generator i and load j can be expressed as follows [24,25,34,35]:

$$\begin{aligned} L_{G_i} &= P_{G_i}\tfrac{\partial L_{total}}{\partial P_{G_i}} = P_{G_i} K_{ITL_i} \\ L_{D_j} &= P_{D_j}\tfrac{\partial L_{total}}{\partial P_{D_j}} = -P_{D_j} K_{ITL_j} \end{aligned} \tag{3}$$

2.2.3. Proportional Sharing Procedure

The proportional sharing procedure, known as a power flow tracing method, is based on a linear proportional sharing principle suggested in [26,31]. The proportional sharing principle assumes that power outflows from the nodes contain the same proportion of the inflows as the total nodal flow [26,31]. Generators' and loads' contributions to losses can be calculated using the upstream- and downstream-looking algorithms, which are based on the proportional sharing principle [26,31]. The upstream-looking algorithm looks at how each generator contributes to the loads and lines by using gross flow analysis, which assumes that the line flow equals the sending end power of the actual line [26,31]. The downstream-looking algorithm looks at how each load is responsible for the generation and lines by using net flow analysis, which assumes that the line flow equals the receiving end power of the actual line [26,31].

To begin with, the upstream matrix A_u that describes the proportion of power that flows to node n of power outflow at the directly connected node m (a component of the set $\alpha_n^{(u)}$), and the downstream matrix A_d that describes the proportion of power that flows from node n of power inflow at the directly connected node l (a component of the set $\alpha_n^{(d)}$) are decided as follows [26–33]:

$$
\begin{aligned}
[A_u]_{nm} &= \begin{cases} 1 & for\ n = m \\ -\frac{|P_{m-n}|}{P_m} & for\ m \in \alpha_n^{(u)} \\ 0 & otherwise \end{cases} \\
[A_d]_{nl} &= \begin{cases} 1 & for\ n = l \\ -\frac{|P_{l-n}|}{P_l} & for\ l \in \alpha_n^{(d)} \\ 0 & otherwise \end{cases}
\end{aligned} \tag{4}
$$

where P_m is the total power outflow at node m while $|P_{m-n}|$ is the magnitude of power flow in line m-n and P_l is the power inflow at node l while $|P_{l-n}|$ is the magnitude of power flow in line l-n [26–33].

By using A_u with an assumption that transmission losses are small, $P_{D_n}^{gross}$, the gross load at node n can be expressed with the contribution of generators at each bus. Likewise, using A_d, $P_{G_n}^{net}$, the net generation at node n can be expressed with the contribution of loads [26–33].

$$
\begin{aligned}
P_{D_n}^{gross} &= \frac{P_{D_n}^{gross}}{P_n^{gross}} P_n^{gross} \cong \frac{P_{L_n}}{P_n^{gross}} \sum_{k=1}^{total} [A_u^{-1}]_{nk} P_{G_k}\ for\ i = 1, 2, \ldots, total \\
P_{G_n}^{net} &= \frac{P_{G_n}^{net}}{P_n^{net}} P_n^{net} \cong \frac{P_{G_n}}{P_n^{net}} \sum_{k=1}^{total} [A_d^{-1}]_{nk} P_{D_k}\ for\ i = 1, 2, \ldots, total
\end{aligned} \tag{5}
$$

In (5), P_n^{gross} is the gross throughflow of node n, P_{G_k} is the kth nodal power in the system, and thus, $[A_u^{-1}]_{nk} P_{G_k}$ shows the contribution of the kth system generator to P_n [26]. Likewise, P_n^{net} is the net throughflow of node n, P_{D_k} is the kth load in the system and thus, $[A_d^{-1}]_{nk} P_{D_k}$ shows the contribution of the kth load to P_n [26]. Then, ΔP_{D_n}, the difference between the gross demand $P_{D_n}^{gross}$ and the actual demand P_{D_n} will be the loss attracted by power flowing from all the generators to a particular load [26]. Likewise, ΔP_{G_n}, the difference between the actual generation P_{G_n} and the net generation $P_{G_n}^{net}$ will be the loss attracted by power flowing from a given generator to all nodes [26].

$$
\begin{aligned}
\Delta P_{D_n} &= P_{D_n}^{gross} - P_{D_n} \\
\Delta P_{G_n} &= P_{G_n} - P_{G_n}^{net}
\end{aligned} \tag{6}
$$

2.3. Needs for a New Loss Management Scheme in P2P Electricity Trading

The conventional loss management schemes described in Section 2.2 have two things in common, regardless of whether they are embedded cost allocation methods or marginal procedures. First, calculation and allocation of losses to generators and loads can be made after network users submit their bids/offers. Second, the network operators play a central role in calculating and allocating the losses to network users.

In order to proceed with the pro-rata procedure in Section 2.2.1, the total losses in the grid L must be obtained first above all else. As total losses L can only be calculated after bids and offers are submitted and matched, we classify the pro-rata procedure as an ex-post loss allocation method, taking the moment of submitting bids and offers as the reference time. The marginal procedure in Section 2.2.2 and the proportional sharing procedure in Section 2.2.3 can be proceeded based on the converged power flow results. Analyzing the power flow of the network is only possible after the bids and offers are submitted and matched. By the same token, the pro-rata procedure and the marginal procedure can also be classified as ex-post loss allocation methods.

In the conventional electricity market where ex-post loss allocation methods in Sections 2.2.1–2.2.3 are used, network users cannot know the losses their transaction will cause. Instead, users accept the loss costs that central network operators calculate and notify during the settlement process following the electricity market's rule. However, these ex-post loss allocation methods and the conventional operator-oriented market are not suitable for P2P electricity trading due to the characteristic of the P2P economy.

Under the P2P economy, also known as the sharing economy, individuals or groups seek to maximize their utility by directly trading underused or overproduced resources [41–44]. Thus, the P2P economy can be maintained and continuously expanded when individuals or groups can easily access the market and predict the benefits of participation. In this regard, participants may favor the minimal mediation of a third-party, which can cause overhead costs and disturb the expected utility calculation.

However, in the conventional loss allocation methods, the network operator allocates the network costs to users after participants' submission of the bids/offers, such that it makes users hard to calculate the expected benefit from the P2P trading. Further, the network operators may bill the overhead costs to participants for their efforts spent for power systems' stable and efficient operation.

3. Loss Management Framework for P2P Electricity Trading

3.1. Market Design Considerations

In Section 2, it is described why the ex-post loss management scheme in the operator-oriented conventional electricity market is not suitable for the P2P economy. Then, which market structure is suitable for P2P electricity trading, and how should the loss management scheme be implemented? From the discussions in Section 2.3, we derive the following requirements that a market for P2P electricity trading must satisfy:

Requirement 1. Peers should be able to participate in the market at any time in case of a surplus or demand of electricity.

Requirement 2. Network operators' mediation on the transaction should be minimized.

Requirement 3. Peers should be able to calculate the benefits of participating in the market before proceeding with the P2P electricity trading.

Requirement 4. The market must not undermine the prerequisite of the "stable and efficient operation of power systems."

As a form of market structure that satisfies Requirement 1 and Requirement 2, the CDA can be considered. The CDA is an auction mechanism where transactions can occur at any time whenever bids and offers match [45]. Among various auction methods, the CDA has been attracting attention as a structure suitable for a decentralized system because it enables efficient resource allocation without the intervention of a centralized auctioneer [43,44,46,47]. Under the structure of CDA, it is difficult for network operators to present a schedule to be followed by all participants or to fulfill the simultaneous market clearing as they have conducted in conventional electricity markets.

In Section 3.2, a new loss management scheme based on the CDA will be presented and examined whether it satisfies the remaining two requirements (Requirement 3 and Requirement 4).

3.2. New Loss Management Scheme with Ex-Ante Allocation

3.2.1. Ex-Ante Loss Allocation by Network Impacts

The new loss management scheme is based on CDA. Under the new scheme, the price of bids/offers submitted through the P2P electricity trading platform is adjusted before it is announced or published to other peers considering the possible losses.

Suppose a producer at bus 1 submits a selling bid of \$0.10/kWh in the 6-bus network example in Figure 1a. Then, as shown in Figure 1a, it is published at different prices to consumers at the other buses. The increased prices at buses 3, 4, and 6 indicate that the transactions between bus 1 and the corresponding nodes will cause more losses. Thus, the associated consumer should pay more than the original price that the producer offered. In contrast, the decrease in the price at buses 2 and 5 implies that the transaction between bus 1 and buses 2 and 5 may relieve a heavy-loaded branch while reducing the power losses in the network. Therefore, the associated consumer will be rewarded by purchasing electricity at a cheaper price.

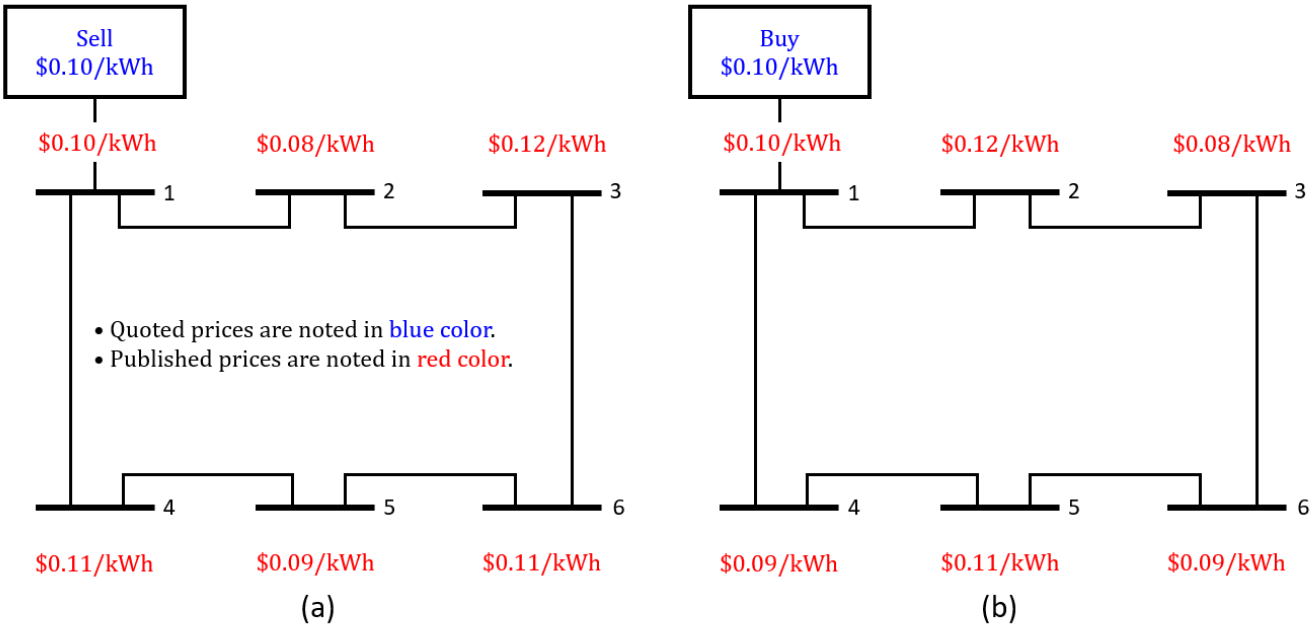


Figure 1. Examples of adjusted prices published to other nodes considering the network impacts: (**a**) offers (**b**) bids.

A similar explanation can be made when a consumer quotes a price for buying electricity. Suppose that a producer at bus 1 in Figure 1b submits a purchasing bid of $0.10/kWh. Then, as shown in Figure 1b, it is published at different prices to producers at other buses. The decreased prices at buses 3, 4, and 6 indicate that the transaction between bus 1 and the corresponding nodes will cause more losses. Thus, the associated producer will be paid less in these cases. In contrast, the increase in the price at buses 2 and 5 implies that the transaction between bus 1 and buses 2 and 5 may relieve a heavy-loaded branch while reducing the power losses in the network. Therefore, the associated producer will be rewarded by selling electricity at a higher price. It should be noted that the adjusted prices considering losses are not proportional to the physical distance between the buses associated with the transaction. The losses are determined by power flows, and they also differ from the operating point of power systems. Thus, the adjusted prices can have the same value at different buses such as buses 4 and 6 in Figure 1.

The price adjustment in the new loss management scheme based on ex-ante loss allocation can be regarded as user-friendly in that it enables peers to calculate the expected utility of market participation by presenting information about the loss costs before the transaction is carried out (Requirement 3). Further, in terms of the allocation of loss costs, the new loss management scheme can be seen to faithfully implement the cost causation principle, compared to the existing embedded cost allocation methods, which focus on cost distribution after delivery. The possibility of conflict during the settlement process can also be reduced in the new scheme because it allows peers to proceed with the transaction while the loss costs included. It should be noted that, on calculating the possible loss costs, various methods have been developed [20,48,49], and developing the new one is not the scope of this paper. In simulating the new loss management scheme in Sections 4–6, we applied basic power flow equations for the loss costs calculation.

3.2.2. Matching Peers in a Transaction

The matching process for completing a transaction is simple in the proposed scheme. At first, buyers/sellers in the network who want to trade electricity submit bids/offers to the P2P electricity platform. Following the procedure in Section 3.2.1, each bid/offer submitted is adjusted for N_{bus} times, where N_{bus} is the number of buses in the network, reflecting the loss costs in the possible transaction between the buyer/seller who submitted the bid/offer and other sellers/buyers in every bus. After the procedure, the information of adjusted prices of bids/offers are sent to each bus. Then, at each bus, those prices are gathered, sorted in descending order as buying/selling order books, and published to sellers/buyers. Finally, the sellers/buyers on each bus select the offer/bid that meets their needs from order books.

For example, as shown in Figure 2, when a producer (a seller) at bus 1 connects the P2P trading platform, the bidding queue of published prices sorted in the merit order, that is, in descending order, is provided to the producer. If the highest price in the queue is greater than the expected selling prices, the producer has only to pick and accept the bid with the highest price. If the highest price is less than the expected price, the producer can choose to submit a new offer with the desired price to the P2P electricity trading platform. Similarly, a consumer (a buyer) has only to pick and accept the offer with the lowest price in the bidding queue if it is less than the expected price; otherwise, the consumer can choose to submit a new bid with the desired price. The matching process described in this subsection is summarized as a flow chart in Figure 3.

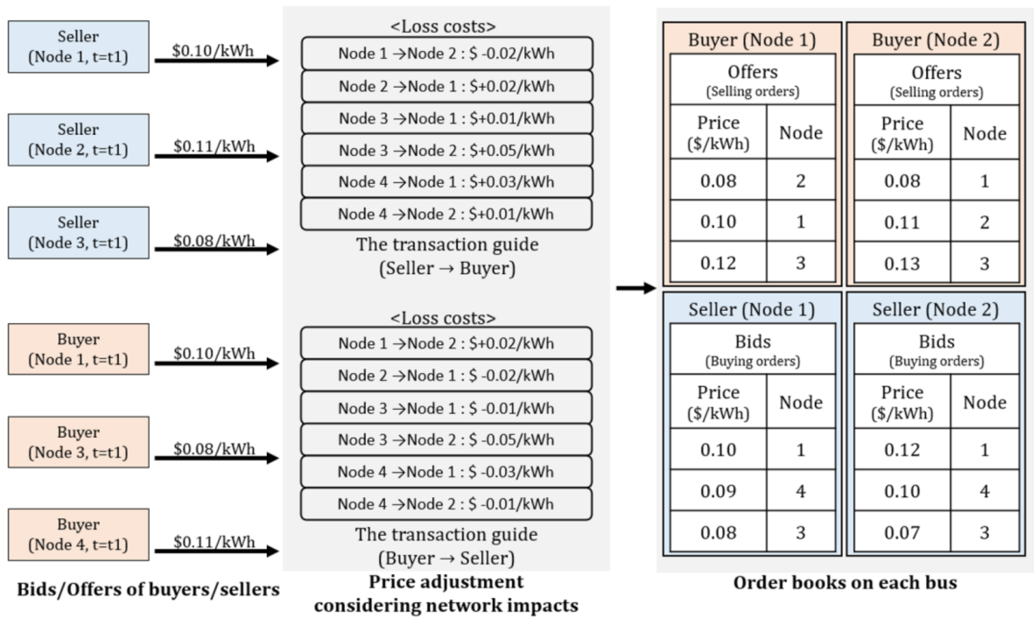


Figure 2. Concept of the matching process using the transaction loss guide.

It should be noted that order books on each bus described in Figure 2 are only limited to time t1. Since a matched transaction could affect the power flowing in the network, the electrical distance between buses continues to change following the progress of other transactions even if the physical properties of the network do not change. Therefore, the published prices of offers or bids that reflect the network losses—the electrical distance—keep changing following the change of power flowing in the network, and thus, the order books on each bus change in real-time.

3.2.3. The New Loss Management Framework and the Transaction Guide

The loss management framework discussed thus far can be expressed as a sequence diagram in Figure 4. The biggest difference between the new loss management framework and the conventional one is that network operators in the former structure do not directly arrange transactions to minimize the network losses, unlike network operators in the latter. The new loss management framework assumes that prosumers always act to maximize their utility and profit. Under this assumption, the new framework just helps prosumers make the rational choice by providing the order book of price-adjusted bids and offers based on the loss costs, therefore, which can be named as a transaction "guide".

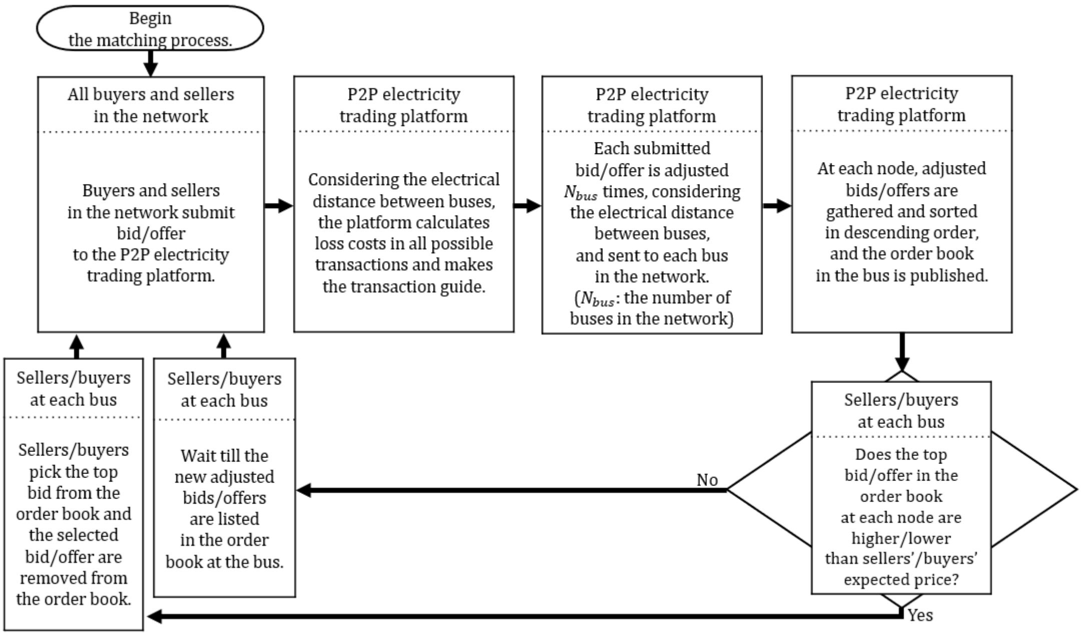


Figure 3. Flow chart of the matching process in the new loss management framework with ex-ante allocation.

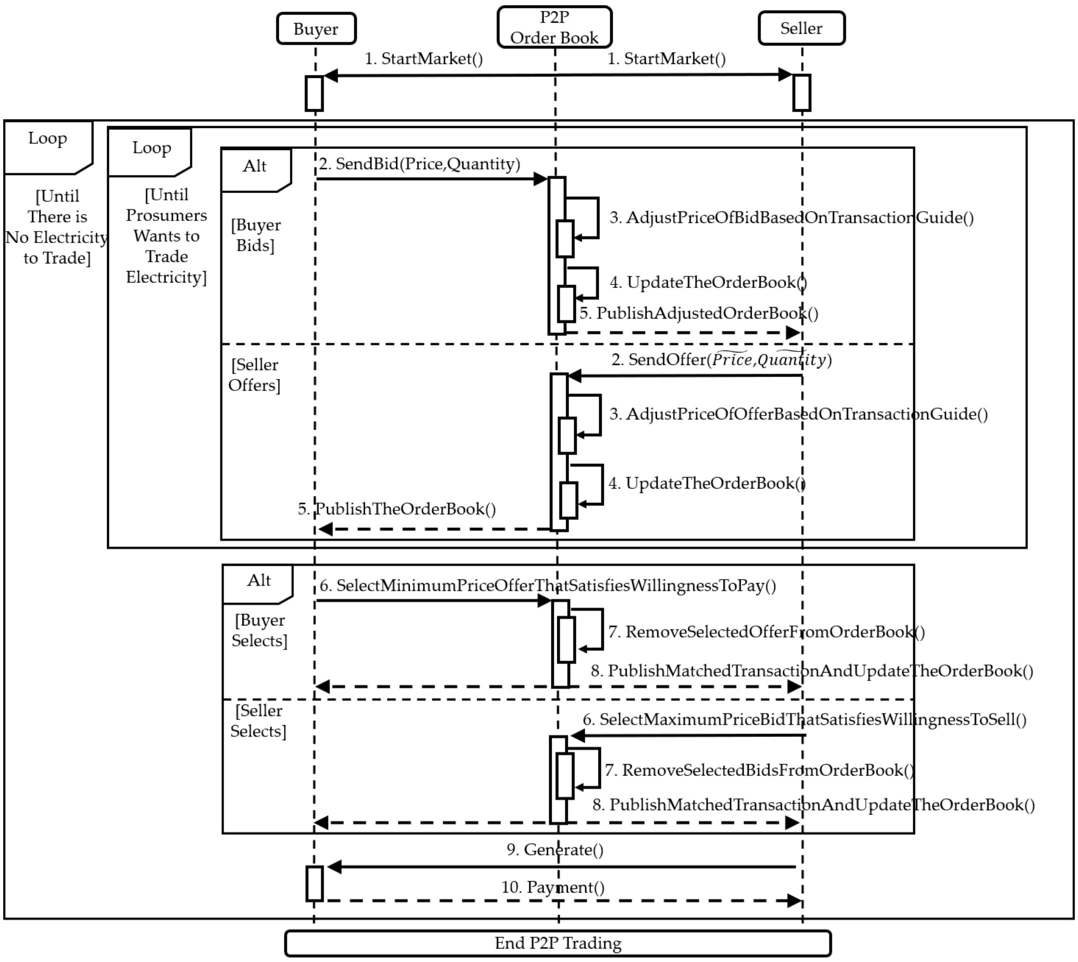


Figure 4. The sequence diagram of the new loss management framework.

The advantage of the transaction guide is that a network-level property can be improved while maintaining the concept and philosophy of decentralized transactions as much as possible. Further, as the transaction guide is an algorithm-based framework and can be automatized, the engagement of the network operator regarding the matter of losses can be minimized. However, since the transaction guide does not force a transaction between a specific producer and a specific consumer, the property is neither optimized nor is it guaranteed that its improvement should be significant compared to the centralized alternatives.

4. Simulation Setup

4.1. Simulation Descriptions

Then, can the new loss management framework, the transaction guide based on CDA suggested in Section 3, be effective in loss minimization in the P2P electricity trading market? What should be considered to improve the effectiveness of the new loss management framework? We examine these questions by simulations using the IEEE 39 bus mesh network and the IEEE 33 radial network. The simulations are carried out using MATLAB [50] and MATPOWER [51]. The simulation environment and the time spent on the simulation are described in Appendix A.

The effectiveness of the new loss management framework is shown by comparing the value of losses calculated in three different ways:

1. (The centralized loss management case). The first value of losses is calculated using the minimum-loss power flow equations. The value is the deterministic result that could be achieved if all the transactions are made in a centralized way. That is, all bids and offers are submitted to the operators before the market closure, and the operators match the bids and offer simultaneously. The centralized way is a dominant matching algorithm in many liberalized electricity markets in the world. We regard the first value as a benchmark to check the performance of other loss management frameworks.
2. (The random transaction case). The second value of losses is calculated not considering the transaction guide but only considering the CDA. That is, prosumers can trade electricity at any time, but they do not consider any losses that can occur during their transactions. The CDA based P2P market, which does not consider losses before the market clearing, is presented in [13,36,37,39,40].
3. (The guided transaction case). The third value of losses is calculated under the new loss management framework in Section 3.2, which considers both CDA and the transaction guide. By comparing the third value with the second value, we present the effectiveness of the new loss management framework in Section 3.2, the transaction guide based on CDA.

4.2. Assumptions

For simplifying simulation, we assumed that only the prosumers with excess electricity submit offers, and those who lack electricity do not submit bids to the platform but just select offers. To focus especially on the loss managing performance of the new framework, we assumed that quoted prices in the bids and all buyers' willingness to pay are all the same. Under the assumptions, buyers in the random transaction case randomly select offers from the order book, but in the guided transaction case, buyers select offers from the order book that all offers are organized by losses in the ascending order. Other important features in electricity market studies, such as welfare analysis, will be dealt with in future works.

Further, in matching bids and offers, we only considered transactions that do not violate network constraints. Therefore, the tested networks, the IEEE 39 bus system and the IEEE 33 bus system, can keep their stability from the beginning to the end during the simulation. Algorithms used in the simulation under these assumptions are described in Section 5.

4.3. Test Cases: The IEEE 39 Bus System and the IEEE 33 Bus System

Test cases used in the simulation, the IEEE 39 bus system and the IEEE 33 bus system, are described in Tables 1 and 2. The IEEE 39 bus system is a mesh network case that has 10 generators and 46 lines. As we concentrate only on the losses, voltage constraints, generation constraints, reactive power constraints are eased without changing the network topology. The IEEE 33 bus system is a radial network that has only 1 generator and 37 lines initially. For the purpose of implementing P2P trading, 12 more generators are added in the test case referring to the previous research [52].

Table 1. Total demand and available supply at each bus in IEEE 39 mesh network case.

Bus Number	Total Demand [MWh]	Available Supply [MWh]	Bus Number	Total Demand [MWh]	Available Supply [MWh]	Bus Number	Total Demand [MWh]	Available Supply [MWh]
1	97.6	0	14	0	0	27	281	0
2	0	0	15	320	0	28	206	0
3	322	0	16	329	0	29	283.5	0
4	500	0	17	0	0	30	0	1040
5	0	0	18	158	0	31	9.2	2000
6	0	0	19	0	0	32	0	725
7	233.8	0	20	680	0	33	0	652
8	522	0	21	274	0	34	0	508
9	6.5	0	22	0	0	35	0	2000
10	0	0	23	247.5	0	36	0	580
11	0	0	24	308.6	0	37	0	564
12	8.53	0	25	224	0	38	0	865
13	0	0	26	139	0	39	1104	2000

Table 2. Total demand and available supply at each bus in IEEE 33 radial network case.

Bus Number	Total Demand [kWh]	Available Supply [kWh]	Bus Number	Total Demand [kWh]	Available Supply [kWh]	Bus Number	Total Demand [kWh]	Available Supply [kWh]
1	0	100	12	60	500	23	90	0
2	100	500	13	60	0	24	420	500
3	90	0	14	120	500	25	420	500
4	120	500	15	60	0	26	60	0
5	60	0	16	60	0	27	60	0
6	60	0	17	60	0	28	60	0
7	200	500	18	90	500	29	120	500
8	200	0	19	90	0	30	200	500
9	60	0	20	90	0	31	150	0
10	60	0	21	90	0	32	210	500
11	45	0	22	90	0	33	60	500

5. Algorithms Used in Simulation

5.1. Algorithms

Buyers' offer selection processes in the random transaction case and the guided transaction case in the simulation are implemented using algorithms written in MATLAB as follows:

1. In the random transaction case, the algorithm randomly allocates the purchase order among the buyers as the P2P electricity trading under the new loss management framework based on CDA has a random characteristic. Then, following the purchase order list, the algorithm randomly matches the buyer in turn with an offer not yet selected and calculates the increase in network losses resulting from the match. The confirmed transaction is added to the network's transaction log, and the buyers who filled their demands through the transactions are excluded from the purchase order

lists. Likewise, the generators who sold all of their electricity are excluded from the pool of offers. The algorithm proceeds till all the buyers finish their purchases. The value of losses in the random transaction case is the sum of each increased loss in every match. Algorithm 1 below is the pseudocode of the logic we used for the random transaction case simulation.

Algorithm 1. Matching algorithm for buyer $i \in N_b$ at time t_τ in the random transaction case.

Input 1: $O^*_{t_\tau}$ for set of matched trade
Input 2: $S_{t_\tau} := \left\{\rho^s_{1,t_\tau}, \rho^s_{2,t_\tau}, \ldots, \rho^s_{j,t_\tau}, \ldots, \rho^s_{N_s,t_\tau}\right\}$ for set of new selling bids from every node
Input 3: $B_{t_\tau} := \left\{p^b_{1,t_\tau}, p^b_{2,t_\tau}, \ldots, p^b_{j,t_\tau}, \ldots, p^b_{N_b,t_\tau}\right\}$ for set of buyers
1: **while** $S_{t_\tau} \neq \varnothing$:
2: choose buyer p^b_{k,t_τ} in the set B_{t_τ};
3: Let temporary set J to $\varnothing$;
4: **for** j = 1 to N_s:
5: $J \leftarrow J \cup \{j\}$;
6: **end**
7: pick random j' from the set J;
8: $S_{t_\tau} \leftarrow S_{t_\tau} - \left\{\rho^s_{j',t_\tau}\right\}$;
9: $O^*_{t_\tau} \leftarrow O^*_{t_\tau} \cup \left\{\left(p^b_{k,t_\tau}, \rho^s_{j',t_\tau}\right)\right\}$;
10: **Return** $O^*_{t_\tau}$;
11: **end**

2. In the guided transaction case, the algorithm randomly allocates the purchase order among the buyers considering the random characteristic of CDA, such as the algorithm in the random transaction case did. However, unlike the random transaction case, the transaction guide described in Section 3.2 is adopted in the guided transaction case. Before the matching process, by solving the power flow equations, the algorithm calculates all possible increases of network losses that a choice of the buyer, in turn, could cause. Under the assumption of the same quoted prices mentioned in Section 4.2, it is the list of calculated network losses that works as the order book in Section 3.2 and "guides" buyers to select the offers. Based on the calculated losses, the algorithm matches the buyer in turn with the offer that minimizes the change of network losses, reflecting the buyer's tendency to maximize utility (Section 3.2.3). The process of the algorithm afterward is the same as the random transaction case. The confirmed transaction is added to the network's transaction log, and the buyers who filled their demands through the transactions are excluded from the purchase order lists. Likewise, the generators who sold all of their electricity are excluded from the pool of offers. The algorithm proceeds till all the buyers finish their purchases. The value of losses in the guided transaction case is the sum of each increased loss in every match. Algorithm 2 below is the pseudocode of the logic we used for the guided transaction case simulation.

Algorithm 2. Matching algorithm for buyer $i \in N_b$ at time t_τ in guided transaction cases.

Input 1: $O^*_{t_\tau}$ for set of matched trade
Input 2: $S_{t_\tau} := \left\{\rho^s_{1,t_\tau}, \rho^s_{2,t_\tau}, \ldots, \rho^s_{j,t_\tau}, \ldots, \rho^s_{N_s,t_\tau}\right\}$ for set of new selling bids from every node
Input 3: $B_{t_\tau} := \left\{p^b_{1,t_\tau}, p^b_{2,t_\tau}, \ldots, p^b_{j,t_\tau}, \ldots, p^b_{N_b,t_\tau}\right\}$ for set of buyers
while $S_{t_\tau} \neq \varnothing$:
    choose buyer p^b_{k,t_τ} from the set B_{t_τ};
    let temporary set L_{t_τ} to $\varnothing$;
    for j = 1 to N_s:
        solve power flow for ρ^s_{j,t_τ};
        calculate total losses L_{j,t_τ};
        $L_{t_\tau} \leftarrow L_{t_\tau} \cup \left\{L_{j,t_\tau}\right\}$;
    end
    pick j′ that minimizes $L_{j\prime,t_\tau}$ in the set L_{t_τ};
    $L \leftarrow L + L_{j\prime,t_\tau}$;
    $S_{t_\tau} \leftarrow S_{t_\tau} - \left\{\rho^s_{j\prime,t_\tau}\right\}$;
    $O^*_{t_\tau} \leftarrow O^*_{t_\tau} \cup \left\{\left(p^b_{k,t_\tau}, \rho^s_{j',t_\tau}\right)\right\}$;
Return $O^*_{t_\tau}$, L;
end

Every time the algorithms are executed, the value of losses may vary because of the random characteristic of the purchase order list. Therefore, in examining the value of losses, we execute each algorithm 100 times and watch the distribution.

5.2. The Transaction Limits

During the simulation of the random transaction case and the guided transaction case, the remainder of the electricity of each generator and the deficit of the electricity of each buyer can affect the overall results. That is, when a generator, which just finished a transaction with a buyer, in turn, does not have any remainder of electricity to sell, the next buyer located electrically near may have to buy electricity from other generators located electrically far.

Therefore, we control the overall demand and supply in the network during the simulation by setting the transaction limit and investigating its effect on the overall transactions and losses by changing it variously. For the mesh network case, the transaction limit varies from 10 MWh (near 0 MWh) to 800 MWh with increments of 50 MWh, and for the radial network case, 5 kWh (near 0 kWh) to 400 kWh with increments of 25 kWh. It should be emphasized that, even if the transaction limit is applied, the total demand of each buyer and the available supply of each generator in Tables 1 and 2 do not change. All buyers could fulfill their demand at the end of the simulation regardless of the transaction limits. The only differences between the simulations with different transaction limits are the number of transactions used to fulfill each buyer's demands.

6. Case Study and Results Analysis

6.1. The Effect of the New Loss Management Scheme and the Appropriate Transaction Limit

The simulation results of the network losses in the guided case and the random case in the IEEE 39 bus system are shown in Figure 5a,b as sets of box plots. In both figures, the minimum network losses of 26.8124 MW in the conventional case, which can be calculated by solving the minimal loss OPF problem through MATPOWER, is presented as a red reference line.

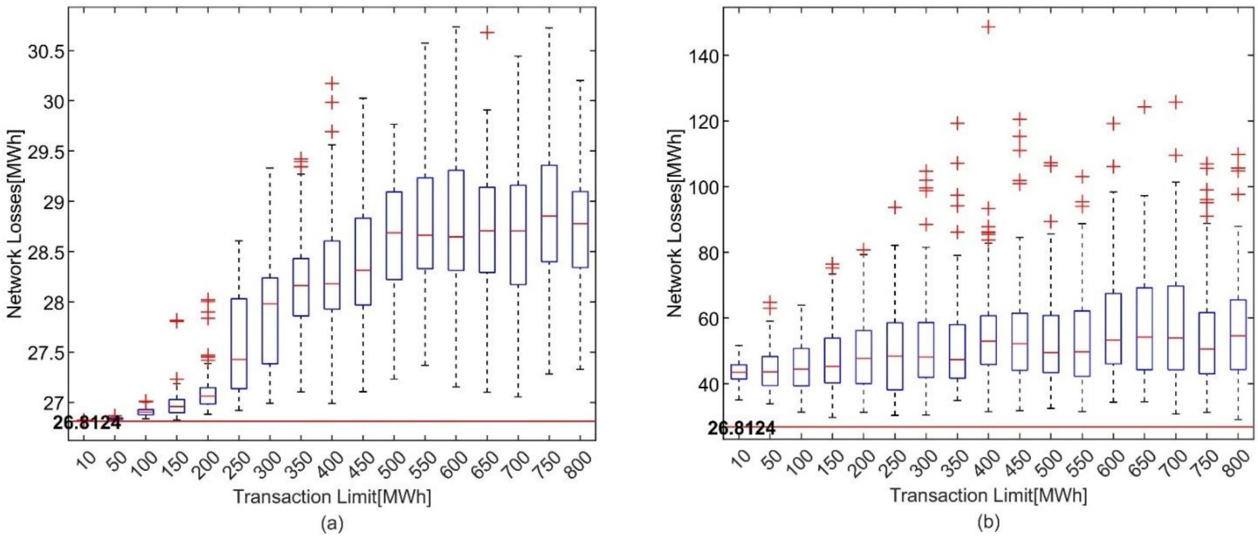


Figure 5. Distribution of network losses in the IEEE 39 bus system: (**a**) the guided case; (**b**) the random case.

As shown in Figure 5a, the network losses in the guided case in the IEEE 39 bus system vary by the transaction limits. When the transaction limit was set to 10 MWh, therefore, all buyers could not buy more than 10 MWh in a transaction, the average network losses for 100 trials were calculated as 26.8143 MWh, which was 0.0070% more than the conventional case, 26.8124 MWh. However, when the transaction limit was 800 MWh, which was the biggest value of the transaction limit set, the average network losses for 100 trials were increased to 28.7611 MWh, which was 7.2681% more than the conventional case. The trend of the average difference ratio of network losses between the conventional case and the guided case shows an increasing trend following the increase of the transaction limit. This implies that when the transaction limit is set to a small value, the new loss management framework for P2P trading can achieve near-optimal results in terms of losses at the network level.

Similar to Figure 5a, the average difference ratio of network losses between the conventional case and the random case in Figure 5b also shows an increasing trend. However, the minimum value of the average difference ratio of network losses between the conventional case and the random case was 62.5977% when the transaction limit was 10 MWh, and the ratio increased to 106.1713% when the transaction limit was 700 MWh, which were both larger than the guided cases.

The effectiveness of the transaction guide is shown in Figure 6 in detail. In Figure 6, the average difference ratio of network losses between the random case and the guided case in the IEEE 39 bus system is presented. In the guided cases, by applying the new loss management framework, the network losses decreased compared to the random cases regardless of overall transaction limits. When the transaction limit was set to 10 MWh, the average network losses in the guided case decreased −38.1644% compared to the random case's network losses. When the transaction limit was set to 700 MWh, the average network losses in the guided case decreased −46.9449% in comparison with the network losses in the random case. The result indicates that P2P trading framework based on CDA but not using the transaction guide cannot achieve the optimal result at the network level, and the random characteristic of P2P trading itself does not guarantee favorable transaction ordering in terms of network losses.

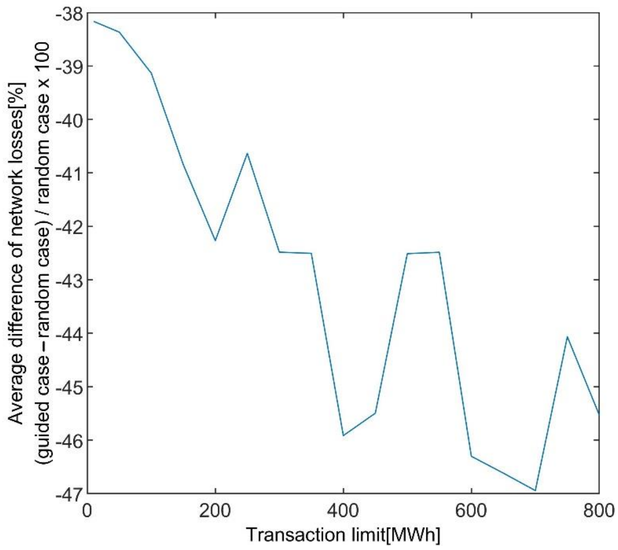


Figure 6. Average difference ratio of network losses between the random case and the guided case in the IEEE 39 bus system.

Similar results are observed in the simulation for the IEEE 33 bus system. The network losses in the conventional case were 62.1362 kWh, as shown in the red horizontal line in Figure 7a, and the network losses in the guided case were 62.1430 kWh, 0.0109% more than the conventional case when the transaction limit was set to be 5 kWh. In the random case in Figure 7b, the value of network losses when the transaction limit was 5 kWh was 67.6283 kWh, 8.838% more than the conventional case. Figure 8 shows the average difference ratio of network losses between the random case and the guided case in the IEEE 33 bus system. Same as Figure 6, the network losses in Figure 8 decreased compared to the random cases regardless of overall transaction limits when the new loss management scheme was applied but the decrease level varied by the transaction limits. When the transaction limit was set to 5 kWh, average network losses in the guided case decreased −8.0712% compared to the random case's network losses. When the transaction limit was set to 400 MWh, the average network losses in the guided case decreased −21.0113% compared to the random case's network losses.

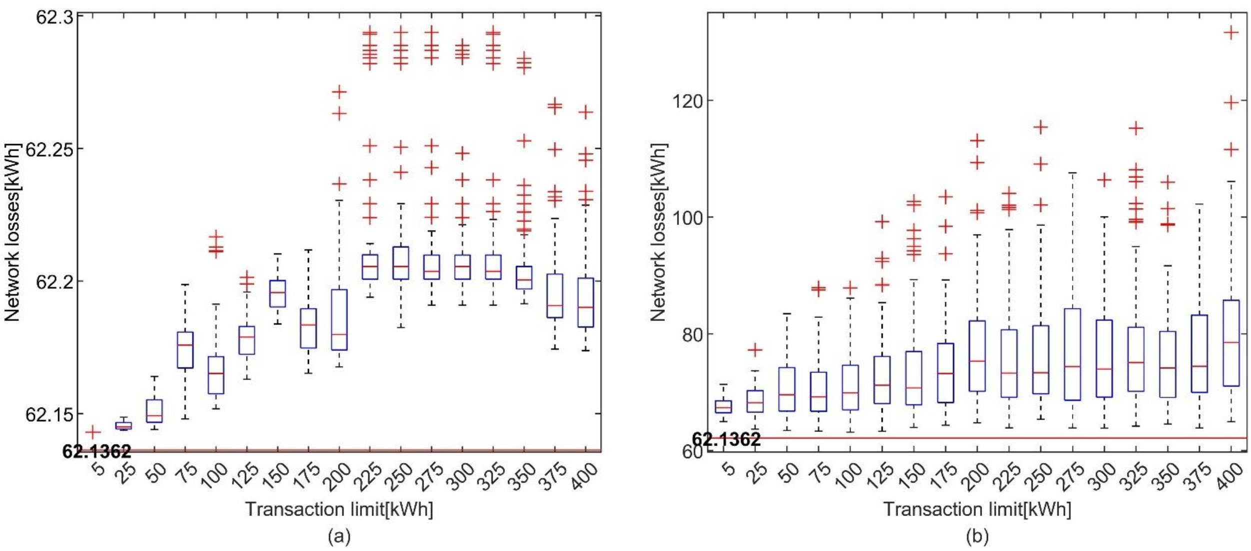


Figure 7. Distribution of network losses in the IEEE 33 bus system: (**a**) the guided case; (**b**) the random case.

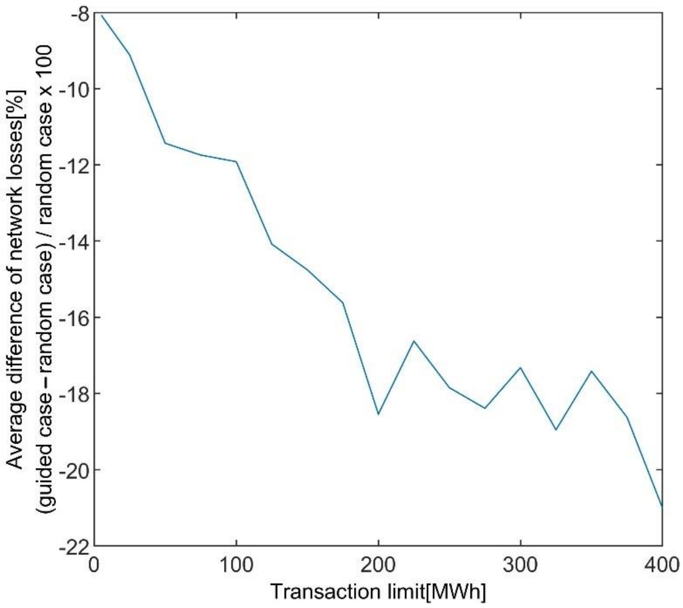


Figure 8. Average difference ratio of network losses between the random case and the guided case in the IEEE 33 bus system.

From the simulation results in this subsection, we can conclude that, regardless of the bus system, the random characteristic of P2P trading itself does not guarantee favorable transaction ordering in terms of network losses, but the new loss management framework based on the transaction guide and CDA can effectively decrease losses. The effect of the new loss management framework can be maximized when the transaction limit is set to an appropriate value.

6.2. The Fair Distribution of Network Losses along the Prosumers

As discussed in Section 3.2, the new loss management framework suggested in this paper aims to minimize the network operators' mediation on the transaction. However, will the new loss management framework allocate the loss costs in a fair way to the prosumers without the network operators' mediation?

During the simulations using the algorithms discussed in Section 5.1, transaction logs of matched bids and offers were made in the random case and the guided case. Through the power flow analysis based on these finished transaction logs of all matched bids and offers in each case, we can derive the total network losses that would be calculated if the central network operator does the allocating process. For the IEEE 39 bus system, the average difference of network losses between the guided case and the power flow analysis based on the finished transaction log was almost zero for every transaction limit. For the IEEE 33 bus system, the average difference of network losses between the guided case and the power flow analysis was zero for every transaction limit. The results are also the same for the random cases. Therefore, in terms of the total loss costs allocated to prosumers, no significant differences can be found between the three cases: the conventional centralized ex-post loss management framework, the guided case, and the random case.

However, the guided case and the random case show different aspects in terms of personal loss costs allocated among each prosumer. To examine the different aspects of loss allocation between the guided case and the random case, we picked a sample transaction log from the 100 trials of simulations in each case and checked the network losses on each transaction. For the IEEE 39 bus system, transaction logs made during the 4th of 100 trials in the guided case and the random case with the transaction limit of 10 MWh were picked, and the network losses on each transaction in the logs are described in Figure 9. As shown in Figure 9a, the range of fluctuation in network losses on each transaction was much bigger in the random case. The range of fluctuation in network losses on each transaction was bigger in the random case. In Figure 9a, the network losses of the guided case ranged from 0 to 0.0141 MWh while the network losses of the random case, −0.0463 to 0.0380 MWh. It means, in random cases, some of the prosumers could obtain much more benefits or penalties than other prosumers in terms of loss costs. Therefore, cumulative network losses increased gradually in the guided case, but in the random case, there were ups and downs in the cumulative network losses, as shown in Figure 9b.

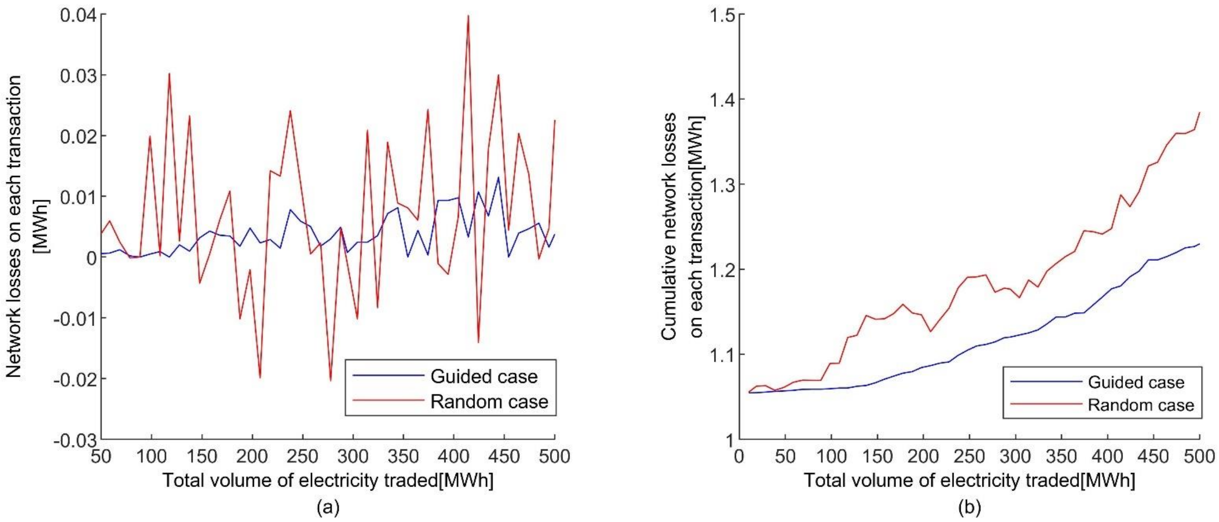


Figure 9. Network losses on each transaction with 10 MWh transaction limit in the IEEE 39 bus case: (**a**) network losses on each transaction; (**b**) cumulative network losses on each transaction.

Similar results were observed in the sample transaction log, the 12th of 100 trials in the guided case and the random case in the IEEE 33 bus system with the transaction limit of 5 kWh. In Figure 10a, the network losses on each transaction in the guided case ranged from −0.0427 kWh to 0.5083 kWh. However, in the random case, the network losses ranged from −4.2828 kWh to 5.2000 kWh. As shown in Figure 10b, there were also ups and downs in the cumulative network losses of the random case, unlike the guided case. Therefore, such as the IEEE 39 bus case, some of the prosumers in the IEEE 33 bus case can obtain benefits or penalties during the P2P trading.

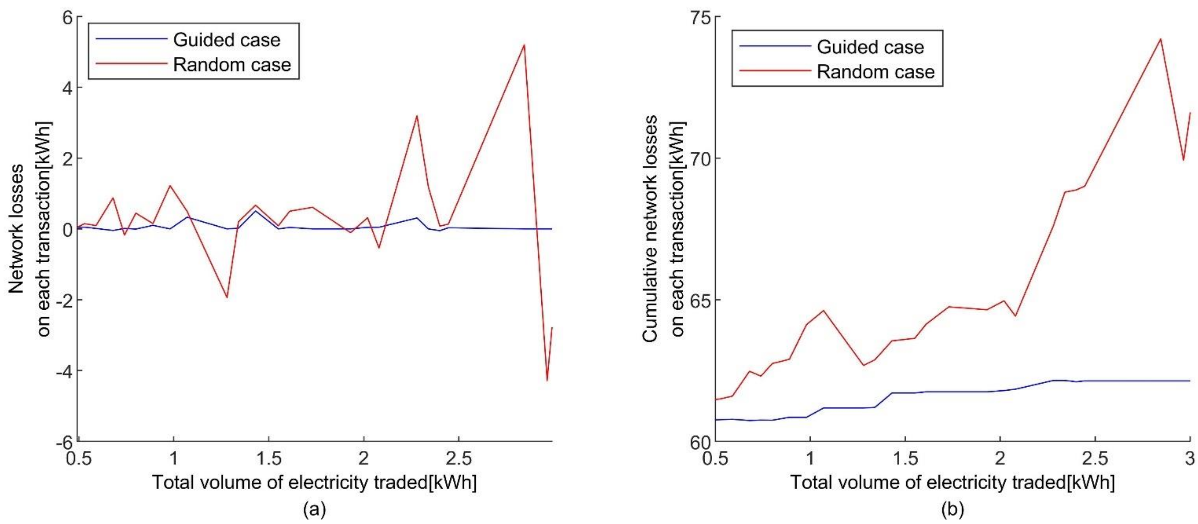
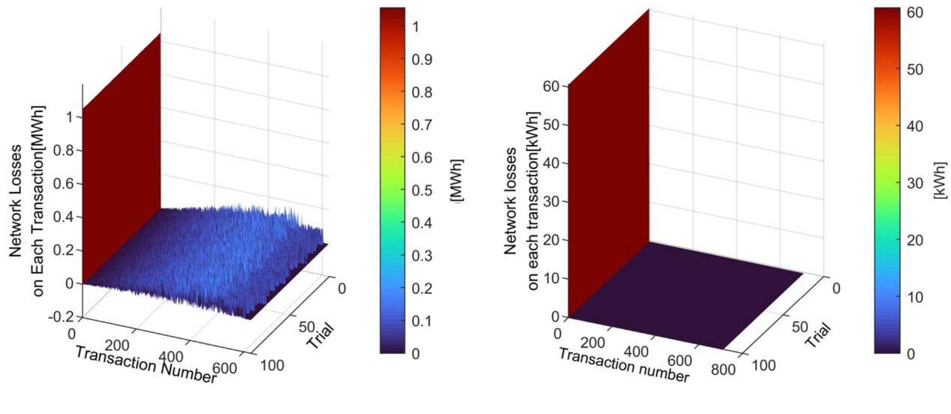


Figure 10. Network losses on each transaction with 5 kWh transaction limit in the IEEE 33 bus case: (**a**) network losses on each transaction; (**b**) cumulative network losses on each transaction.

6.3. The Distribution Characteristic of Network Losses Depending on the Transaction Number

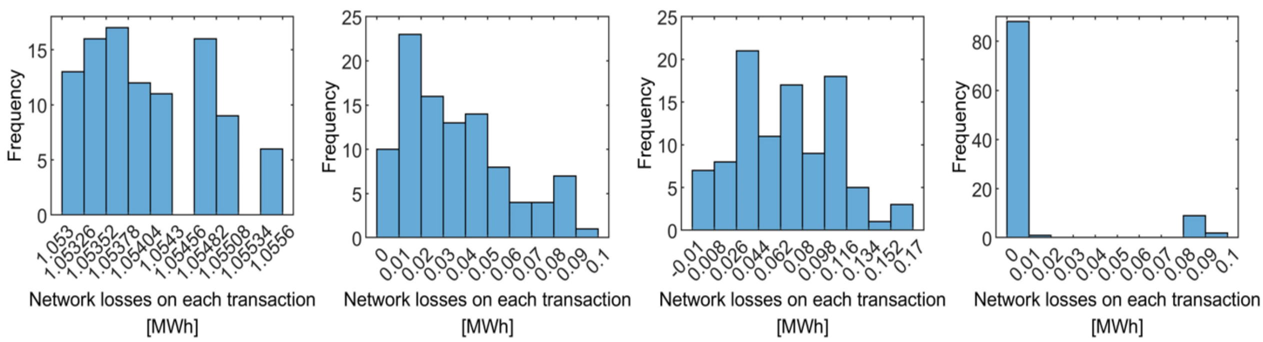
Because of the random characteristic of the ordering process in algorithms used in the guided case and the random case, the network losses on each transaction varied in each trial and transaction number. Even so, in the guided case, the distribution characteristic of network losses showed a specific trend regardless of the bus system, as described in Figure 11.



(a) (b)

Figure 11. Network Loss depending on the transaction number for the 100 trials of the guided case simulations: (**a**) the IEEE 39 bus case with the transaction limit 50 MWh; (**b**) the IEEE 33 bus case with the transaction limit 5 kWh.

Figure 11a is a graph of 100 trials of the network losses on each transaction in the guided cases simulated with the IEEE 39 bus system, and the 50 MWh of the transaction limit and Figure 12 are histograms of network losses of selected transaction numbers (#1, #200, #400 and #600) during 100 trials of simulation. No matter who the first buyer is, as depicted in Figure 11a, the network losses are maximized when the transaction number is 1. The network losses on each transaction for every trial when the transaction number is 1 are distributed from 1.0530 MWh to 1.0556 MWh as shown in Figure 12a, and their average is 1.0540 MWh. However, the average network losses in other order numbers ranged from 0 to 0.0808 MWh. For example, network losses of the #200 transactions on 100 trials ranged between 0 to 0.1000 MWh, network losses of the #400 transactions on 100 trials ranged between −0.0100 MWh to 0.1700 MWh, and network losses of the #600 transactions on 100 trials ranged between 0 to 0.1000 MWh as shown in Figure 12b–d.



(a) (b) (c) (d)

Figure 12. Histograms of network losses of selected transaction numbers in 100 trials of the guided case simulations with the IEEE 39 bus case and the transaction limit 50 MWh: (**a**) network losses of the #1 transactions in 100 trials; (**b**) network losses of the #200 transactions in 100 trials; (**c**) network losses of the #400 transactions in 100 trials; (**d**) network losses of the #600 transactions in 100 trials.

Figure 11b is a graph of 100 trials of the network losses on each transaction in the guided cases simulated with the IEEE 33 bus system, and the 10 kWh of the transaction limit and Figure 13 are histograms of network losses of selected transaction numbers (#1, #200, #400, and #600) during 100 trials of simulation. The graph shows the same trend such as the one in Figure 11a, and the network losses on each transaction are maximized when the transaction number is 1. In this case, the network losses on each transaction for every trial when the transaction number is 1 ranged between 60.6410 kWh to 60.6530 kWh as shown in Figure 13a, and their average is 60.6491 kWh. However, the average network losses in other order numbers ranged from 0.0013 kWh to 0.0032 kWh. For example, network losses of the #200 transactions on 100 trials ranged between −0.0010 kWh to 0.0200 kWh, network losses of the #400 transactions on 100 trials ranged between −0020 kWh to 0.0290 kWh, and network losses of the #600 transactions on 100 trials ranged between −0.0009 kWh to 0.0101 kWh as shown in Figure 13b–d.

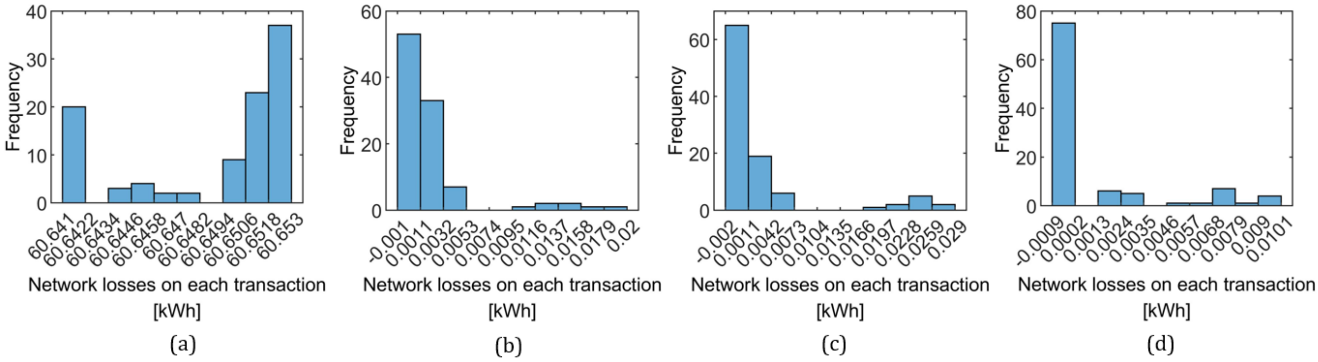


Figure 13. Histograms of network losses of selected transaction numbers in 100 trials of the guided case simulations with the IEEE 33 bus case and the transaction limit 5 kWh: (**a**) network losses of the #1 transactions in 100 trials; (**b**) network losses of the #200 transactions in 100 trials; (**c**) network losses of the #400 transactions in 100 trials; (**d**) network losses of the #600 transactions in 100 trials.

The results imply that, despite the randomness of P2P electricity trading, to the first prosumer, excessive loss costs can be allocated regardless of the bus system. It is because, unlike the other prosumers who can sometimes obtain benefits due to the power flowing status in the network, such as reversed power flow in the network, the first prosumers who make the "priming" power flow in the network can never obtain those benefits. These first excessive loss costs can make prosumers hesitate to participate actively in P2P trading. Therefore, to invigorate the P2P trading in the network and maximize its benefits, an incentive program should be considered for the first mover in the P2P electricity trading.

7. Conclusions

Following the increase of DERs, P2P electricity trading is getting attention to utilize the flexibility and efficiency of decentralized power systems. Some electricity companies have already introduced P2P electricity trading projects thus far, but most of them are still in the beginning stage as there are challenges to be addressed to fully enjoy the benefits of P2P electricity trading. Among the various challenges, this study focused on the problem of network losses.

In the conventional power system, network losses were managed in a centralized way by the network operator. Losses were calculated and allocated to network users in ex-post way. However, the conventional way of managing losses is not suitable for P2P electricity trading, where network users seek to maximize their utility by directly trading underused or overproduced resources. Therefore, we suggested four properties required for the market for P2P electricity trading, designed a new loss management framework that reflected the four requirements and introduced the concept of the transaction guide that enables managing losses in an ex-ante way.

Three noteworthy remarks are derived from the simulation results on P2P electricity trading in this study. First, the random characteristics of P2P trading itself do not guarantee favorable transaction ordering in terms of network losses. However, when the new loss management framework with a transaction guide is applied to the P2P electricity trading, the network losses are effectively decreased. Second, through the new loss management scheme, the loss costs can be fairly allocated to individual prosumers. Third, to invigorate the P2P electricity trading, an incentive program should be considered to alleviate the burden of loss costs of the first trader.

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Data Availability Statement: Publicly available MATPOWER case files were used and modified in this study. MATPOWER case files are included in the zip file of the "Current Release Version" of the MATPOWER and can be downloaded from here: https://matpower.org/download, accessed on 20 July 2021.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Acronyms	
RES	Renewable energy sources
DERs	Distributed energy resources
AMI	Advanced measurement infrastructure
ICTs	Information and communications technologies
P2P	Peer-to-peer
OPF	Optimal power flow
CDA	Continuous double auction
ITL	Incremental transmission loss
Indices	
i	Index of generator number
j	Index of load number
k, n, m, l	Index of node number
τ	Index of time
Parameters and variables	
N_{bus}	The number of buses in the electricity network
L	The total Losses to be allocated to generators and loads [Wh]
L_{G_i}	The losses allocated to generator i [Wh]
L_{D_j}	The losses allocated to demand j [Wh]
K_G	The generation loss allocation factor
K_D	The demand loss allocation factor
K_{ITL_i}	A change in total losses attracted by an incremental change in the power injected in the bus i [Wh]
L_{total}	Total losses [Wh]
A_u	Upstream matrix that describes the proportion of power
A_d	Downstream matrix that describes the proportion of power
P_m	The total power outflow at node m [Wh]

P_l	The power inflow at node l [Wh]
α_n	The set of nodes directly connected to node n
$\lvert P_{m-n}\rvert$	The magnitude of power flow in line m-n [Wh]
$\lvert P_{l-n}\rvert$	The magnitude of power flow in line l-n [Wh]
$P_{D_n}^{gross}$	The gross load at node n [Wh]
P_n^{gross}	The gross throughflow of node n [Wh]
P_{G_k}	The kth nodal power in the system [Wh]
$P_{G_n}^{net}$	The net generation at node n [Wh]
P_n^{net}	The net throughflow of node n [Wh]
P_{D_k}	The kth load in the system [Wh]
ΔP_{D_n}	The difference between the gross demand and the actual demand [Wh]
ΔP_{G_n}	The difference between the actual generation and the net generation [Wh]
N_b	The set of buyer nodes
$O_{t_\tau}^*$	The set of matched trades at time t_τ
S_{t_τ}	The set of new selling bids from every node at time t_τ
B_{t_τ}	The set of buyers at time t_τ
ρ_{m,t_τ}^s	The bids from node m at time t_τ
ρ_{m,t_τ}^b	The offers from node m at time t_τ

Appendix A

For the simulation, we used a laptop computer with Intel(R) Core(TM) i7-9750HF CPU @ 2.60 GHz (12 CPUs), 16G RAM, and MATLAB R2021a software installed on Windows 10 Home 64-bit. In the IEEE 39 network case, with the smallest transaction limit of 10 MWh, it took a total 30.1 s to finish 1 sample trial of simulation of the guided case and random case. When the transaction limit was set to 50 MWh, the time decreased to 6.6 s, 100 MWh, 2.7 s, 150 MWh, 2.1 s, 200 MWh, 2.1 s, 250 MWh, 1.9 s, 300 MWh, 1.5 s, 350 MWh, 1.4 s, and 400 MWh, 1.3 s. In the IEEE 33 network case, with the smallest transaction limit of 5 kWh, it took a total 59.0 s to finish 1 sample trial of simulation of the guided case and random case. When the transaction limit was set to 25 kWh, the time decreased to 7.1 s, 50 kWh, 3.8 s, 75 kWh, 2.6 s, 100 kWh, 2.4 s, 125 kWh, 1.8 s, 150 kWh, 1.7 s, 175 MWh, 1.5 s, and 200 kWh, 1.4 s.

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