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Pricing and Operation Strategy for Peer-to-Peer Energy Trading Using Distribution System Usage Charge and Game Theoretic Model

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ABSTRACT This paper proposes a game-theoretic model for peer-to-peer (P2P) energy trading between a consumer and a prosumer living in a community. The proposed real-time pricing model is based on the Stackelberg game, and the consumer and prosumer are the follower and leader in the game, respectively. Therefore, the prosumer first proposes the trading price and then proposes the trading quantity based on the optimal scheduling of the energy storage system considering the determined trading price, load profile, P2P trading demand, etc. Subsequently, the consumer decides to purchase quantity by adjusting his/her load usage according to the trading price and quantity suggested by the prosumer. In this regard, a power flow analysis was conducted based on the participants' bidding strategy to analyze the changes in the electricity flow in a distribution system in which P2P energy trading occurs. Consequently, changes in power flow from the point of common coupling before and after P2P trading were verified, and the voltage stability of each bus was confirmed. In addition, the distribution system usage charge was calculated to reduce the operational burden of the distribution system operator and suggest an operation strategy that can enable P2P energy trading.

INDEX TERMS Game-theoretic approach, Stackelberg game theory, distribution system operator, power flow analysis, peer-to-peer energy trading.

ABBREVIATIONS AND NOMENCLATURE

A. ABBREVIATIONS

P2P	*Peer to Peer*
DER	*Distributed Energy Resource*
PV	*Photovoltaic*
DSO	*Distribution System Operator*
ESS	*Energy Storage System*
PCC	*Point of Common Coupling*
SOC	*State of Charge*
DSUC	*Distribution System Usage Charge*
SMP	*System Marginal Price*

B. NOMENCLATURE

$\lambda_{j,t}$	*P2P trading price of prosumer j at time t*
$\lambda_{up,t}$	*Import price from the utility at time t*
$\lambda_{low,t}$	*Export price to the utility at time t*
γ	*Price update parameter*
$P_{j,t}^{req}$	*Required demand of prosumer j at time t*
$P_{j,t}^{exc}$	*Surplus power of prosumer j at time t*
$R_{j,t}(\cdot)$	*Revenue function of prosumer j at time t*
$U_{j,t}(\cdot)$	*Utility function of prosumer j at time t*
p_j	*Load consumption preference parameter of prosumer j*
$P_{j,t}^{load}$	*Load consumption of prosumer j at time t [kW]*
$P_{j,t}^{P2P}$	*P2P trading power of prosumer j at time t [kW]*
$P_{j,t}^{grid,buy}$	*Imported power from the utility of prosumer j at time t*
$P_{j,t}^{grid,sell}$	*Exported power to the grid of prosumer j at time t*
$P_{j,t}^{gen}$	*Generated power of prosumer j at time t*

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$P_{j,t}^{cha}$	ESS charging power of prosumer j at time t
$P_{j,t}^{dch}$	ESS discharging power of prosumer j at time t
$SOC_{j,t}$	ESS SOC of prosumer j at time t
t^{step}	time step
η^{dch}	ESS discharging efficiency
η^{cha}	ESS charging efficiency
E_j^{rate}	ESS rated capacity of prosumer j [kWh]
$SOC_{j,T}$	Final SOC level [%]
$SOC_{j,0}$	Initial SOC level [%]
SOC_j^{min}	Minimum SOC of prosumer j [%]
SOC_j^{max}	Maximum SOC of prosumer j
P_{max}^{grid}	Maximum constraint of power from the grid
P_j^{rate}	ESS rated power of prosumer j [kW]
$u_{j,t}^{cha}$	Charge state variable of prosumer j at time t
$u_{j,t}^{dch}$	Discharge state variable of prosumer j at time t
$u_{j,t}^{grid,buy}$	Buying state variable of prosumer j at time t
$u_{j,t}^{grid,sell}$	Selling state variable of prosumer j at time t
$R_{i,t}(\cdot)$	Revenue function of consumer i
$U_{i,t}(\cdot)$	Utility function of consumer i
$P_{i,t}^{P2P}$	P2P trading power of consumer i at time t
$\alpha_{j,t}$	Participation rate of prosumer j at time t
$P_{i,t}^{grid,buy}$	Imported power from the utility of consumer i at time t
$p_{i,t}$	Load consumption preference parameter of consumer i
$P_{i,t}^{load}$	Load consumption of consumer i at time t
$P_{i,t}^{change}$	Load adjustment of consumer i at time t
d_i	Discomfort parameter of consumer i
σ_1	Participation update parameter
γ_{base}	Voltage difference before P2P trading
γ_{P2P}	Voltage difference after P2P trading
V_{base}	Bus voltage before P2P trading
V_{P2P}	Bus voltage after P2P trading
φ_p	Total DSUC
φ_{base}	Basic rate of DSUC
φ_{charge}	Charging rate of DSUC

I. INTRODUCTION

Power systems are crucial for modern economic growth. Recently, economic growth and power consumption are increasing proportionally. However, owing to the limitations of the traditional power system operated by large centralized power plants, new power systems have attracted considerable attention [1]–[4]. Moreover, with the expansion in the strategic demand and the increase in the proportion of renewable energy (whose supply is difficult to control) in the energy mix, the stability of the power system can no longer be secured by existing power generation facilities and vertical power supply systems [5]–[7]. Therefore, the conversion of a power supply system into a distributed energy resource (DER) has been undertaken to secure supply flexibility [8], [9]. So far, a small number of large-scale power plants have accounted for the entire power supply; however, a system of several small power plants is being established, enabling more flexible supply regulation to meet the changing demand.

The distributed power generation system, once established, is expected to minimize the risks of the power system due to the irregular supply of renewable energy via the installation of facilities such as solar and wind power at the optimal power generation site. These facilities mainly include small-scale photovoltaic (PV) systems and small-scale wind power systems, which are connected to the distribution system, and rooftop PV systems, which are being actively installed [10]–[13]. Various policies have been established to encourage the installation of DERs owing to their various benefits.

With the increase in the number of small-scale PV installations, a new type of participant called the PV prosumer has appeared in the energy market [14]–[17]. Various policies have been established to ensure the profitability of prosumers. Among them peer-to-peer (P2P) energy trading is considered the most effective way. Efforts to deal with the prosumer's energy management problem can be categorized into two groups: energy market bidding and dynamic pricing. Considering that the community is too small to be organized as a complicated bidding market, the dynamic pricing model has been emphasized. Assuming that both consumers and prosumers are rational, the trading participants will maximize their profits in response to dynamic prices. The pricing model can be designed based on different approaches such as game-theoretic methods, optimization, and reinforcement learning.

Among them, Stackelberg game is attracting attention as one of the most effective methodologies because it is suitable for designing a price model in a smart grid with a leader-follower structure, i.e., a multi-microgrid or a small community [15]–[18].

Recently, the trend of P2P energy trading research is considering the stability of distribution system as the optimal bidding strategy for energy trading. Li *et al.* [19] has proposed an energy trading model that considers both the economic and technical issues in the distribution system. Liang and Su [17] proposed an optimal bidding strategy to ensure the prosumer's profitability while ensuring the reliable operation of the distribution system. In this study, the authors assumed that the distribution system operator (DSO), who manages the distribution network, performs supply and demand coordination through transactions with the main system, considering the prosumers' bids. A game-theory-based power trading market operation was developed, and a Nash equilibrium point was derived using a relaxation algorithm through a bi-level algorithm and the Nikaido–Isoda function. In this process, the Karush–Kuhn–Tucker condition was applied to derive the optimal bidding strategy considering the distribution system constraints. However, because the individual trading participants need to know information about the distribution system, it is limited to consider the stability of the distribution system as a limiting condition. In addition, determining the optimal strategy without considering the stability of the distribution system is not purely optimal for P2P trading participants.

As the P2P trading becomes active, the utility company's revenues decrease, and there is also a problem of increasing the burden due to the deterioration of system stability and bidirectional power flow caused by the grid connection of small scale renewable energy sources [19].

A number of previous studies have been conducted to introduce P2P trading methods based on game theory. In particular, the Stackelberg game was used to model the multi-level decision making process of the participants in the leader-follower structure in the oligopoly market. Each participant of the game tries to make its best decision to maximize its utility.

In this paper, an innovative game-theoretic P2P energy trading mechanism is proposed for a prosumer-centric model. In the Stackelberg game, the trading price and quantity of electricity are set as interactive variables. In this model, the prosumer acts as a leader, and determines the trading price and quantity, whereas the consumer acts as a follower, and adjusts its behavior in response to the prosumer's strategy. In addition, based on the optimal trading quantity derived from dynamic pricing, we perform power flow analysis to analyze the impact on the distribution system. Accordingly, we propose an operational strategy to reduce the operating burden of the system operator by suggesting a distribution system usage charge.

The main contributions of this paper are summarized as follows:

- A game-theoretic model is proposed for P2P energy trading between prosumers and consumers considering the energy storage system ESS) applications.
- An ESS optimal scheduling scheme is investigated to maximize the trading revenue.
- Power flow analysis is performed to analyze the impact on the system before and after P2P trading, based on the optimal bidding strategy of the trading participants.
- A method of deriving the distribution system usage charge based on the results of the power flow analysis is proposed.

II. SYSTEM CONFIGURATION

Figure 1 presents an overview of the prosumer-centric distribution system, which consists of four main components: 1) prosumers; 2) consumers; 3) P2P marker operator; and 4) DSO. All the prosumers and consumers in a community are connected via bidirectional power and communication links. In the figure, a solid line indicates a physically connected power line, and a dotted line indicates a communication line. Furthermore, the community connects to the upstream utility grid through a point of common coupling (PCC).

In the proposed structure, the consumer is an electricity user without power generation facilities, and the prosumer owns a PV generator and an ESS, which allows it to control and store the generated power actively. Information on energy transactions must be transmitted to the DSO to trade in the

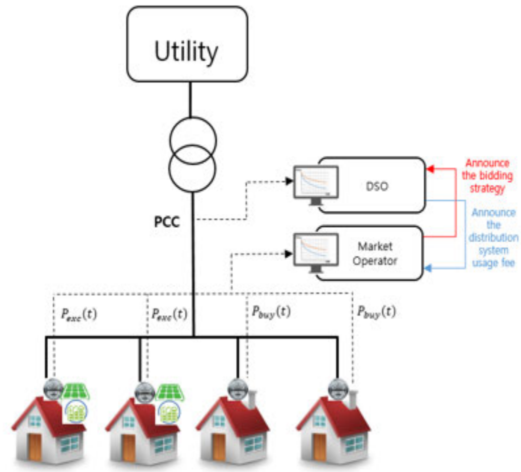

FIGURE 1. A framework of P2P energy trading in a distribution system.

proposed structure, which is a difficult task for individual prosumers and consumers. Consequently, P2P market operators assist in P2P trading, gathering the bidding strategies of individual participants and informing the DSO.

The DSO owns the distribution system infrastructure and is responsible for the reliable and stable operation of the distribution system. Moreover, the DSO approves the P2P market based on the participants' bidding strategies gathered by the P2P market operators. Thus, the DSO secures economic feasibility by charging distribution system usage charges for equipment rentals to prosumers, generating revenue by using the distribution system infrastructure.

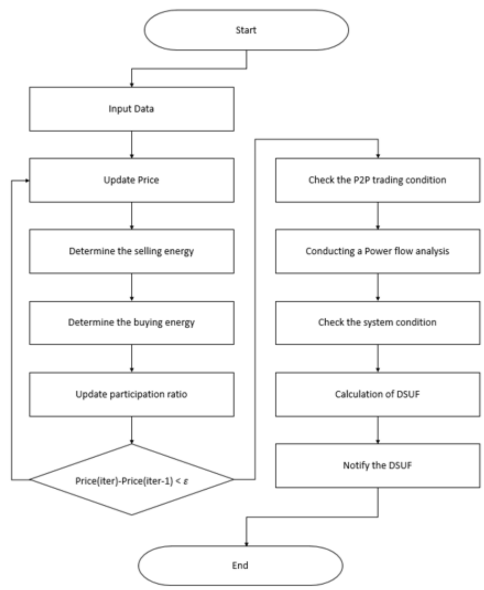

FIGURE 2. Flowchart of the P2P energy trading algorithm.

Figure 2 shows the main flowchart for deriving the optimal bidding strategy of the trading participants. In the proposed P2P trading model, multi-player trading is assumed considering N-prosumers and M-consumers. At this time, the interaction between the prosumer and the consumer was modeled as a Stackelberg game. In this model, the seller is the leader of the game and their strategy is to update the selling price($\lambda_{j,t}$). The price was assumed to be determined by free competition among prosumers. Therefore, as shown in Equation (1), the leader adjusts the price by comparing the demand allocated to him with the supply determined through his surplus power.

After the seller decides the price as a strategy, they decide the optimal trading quantity($P^{P2P}_{j,t}$) in consideration of his utility. This is determined according to Equation (2). In the proposed method, the buyer is a follower who updates his strategy considering the seller's price and quantity. Therefore, the price and quantity suggested by the sellers are input variables of the purchase quantity determination algorithm, and the optimal purchase quantity considering the utility of the buyer is calculated.

In other words, the seller's trading price and quantity influence the determination of the buyer's P2P trading quantity. For example, if the seller suggests the selling price very high, considering only his own revenue, the buyer may react to reducing the P2P trading quantity, resulting in a decrease in sales profit. Therefore, it is important for the seller to establish an appropriate strategy considering the followers' reaction according to his strategy as a leader of the game.

In addition, as a final step of the overall algorithm proposed in this paper, buyers make their own strategies considering the seller's strategy. In the buyer's strategy, the seller participation ratio is updated according to the Equation (28). This participation ratio affects the amount of demand allocated to the seller. In other words, it also affects the buyer's strategy decision of the seller.

The above process is repeated until the price converges, and the power flow analysis is performed according to the P2P trading quantity under the condition where the price converged, and the *DSUC* is determined according to how it affects the system.

A. DETERMINATION OF THE TRADING PRICE

As explained earlier, it is assumed that the free competition market principle determines the selling price among the prosumers. Therefore, it was assumed that the principle of the market price in a competitive market follows 'law of demand and supply', and based on this, it was calculated as Equation (1).

Through this, if the demand for prosumers is greater than their excess power generation, the price is high. In addition, in the opposite case, that is, when the supply is more than the demand, the strategy is to increase the sales revenue by lowering the price. Here, demand requested for each prosumer at time t is determined by the participation ratio, which is the buyer's strategy. That is, it can be seen that the seller's strategy affects the buyer's strategy and vice versa.

$$\lambda_{j,t} = \frac{\lambda_{up,t} + \lambda_{low,t}}{2} + \gamma \times (P^{req}_{j,t} - P^{exc}_{j,t}) \tag{1}$$

B. DETERMINATION OF THE SALES QUANTITY

After the price is determined, individual prosumers determine to schedule to maximize their utility, considering their surplus power, load consumption, required demand, grid energy price, P2P trading price, etc. This results in the determination of the quantity traded in one hour to maximize the prosumers' revenue. The objective function and constraints for determining the sales quantity of the prosumers are as follows:

$$Max \left\{R_{j,t}\right\} = U_{j,t} + P^{P2P}_{j,t} \times \lambda_{j,t} - P^{grid,buy}_{j,t} \times \lambda_{up,t} + P^{grid,sell}_{j,t} \times \lambda_{low,t} \tag{2}$$

$$U_{j,t} = p_j \times ln(P^{load}_{j,t}) \tag{3}$$

$$\text{subject to } P^{gen}_{j,t} + P^{grid,buy}_{j,t} - P^{grid,sell}_{j,t} - P^{ch}_{j,t} + P^{dch}_{j,t} = P^{reg}_{j,t} + P^{load}_{j,t} \tag{4}$$

$$SOC_{j,t} = SOC_{j,t-1} + \frac{\eta_{cha} P^{cha}_{j,t} - (1/\eta_{dch}) P^{dch}_{j,t}}{E^{rate}_j} t^{step} \tag{5}$$

$$SOC_{j,T} = SOC_{j,0} \tag{6}$$

$$P^{cha}_{j,t} \times u^{cha}_{j,t} \leq P^{rate}_j \tag{7}$$

$$P^{dch}_{j,t} \times u^{dch}_{j,t} \leq P^{rate}_j \tag{8}$$

$$P^{grid,buy}_{j,t} \times u^{grid,buy}_{j,t} \leq P^{grid}_{max} \tag{9}$$

$$P^{grid,sell}_{j,t} \times u^{grid,sell}_{j,t} \leq P^{grid}_{max} \tag{10}$$

$$0 \leq P^{grid,buy}_{j,t} \leq P^{grid}_{max} \tag{11}$$

$$0 \leq P^{grid,sell}_{j,t} \leq P^{grid}_{max} \tag{12}$$

$$0 \leq P^{cha}_{j,t} \leq P^{rate}_j \tag{13}$$

$$0 \leq P^{dch}_{j,t} \leq P^{rate}_j \tag{14}$$

$$SOC^{min}_j \leq SOC_{j,t} \leq SOC^{max}_j \tag{15}$$

$$u^{cha}_{j,t} + u^{dch}_{j,t} \leq 1 \tag{16}$$

$$u^{grid,sell}_{j,t} + u^{grid,buy}_{j,t} \leq 1 \tag{17}$$

$$0 \leq u^{cha}_{j,t} \leq 1 \tag{18}$$

$$0 \leq u^{dch}_{j,t} \leq 1 \tag{19}$$

$$0 \leq u^{grid,buy}_{j,t} \leq 1 \tag{20}$$

$$0 \leq u^{grid,sell}_{j,t} \leq 1 \tag{21}$$

In (3), $U_{j,t}$ indicates the utility according to the load consumption of the individual prosumers. In general, satisfaction with load consumption is expressed by the logarithmic or quadratic function according to the law of diminishing marginal utility. Note that p_j is a preference parameter indicating the prosumer j's preference for load consumption, which changes according to the prosumer's unique characteristics. For example, if the utility parameter p_j has a large value, it indicates a prosumer with a high utility for energy consumption. Thus, the prosumer's overall profit is expressed as (2), which combines the cost of transaction with the system and P2P trading with its utility. Equations (4) to (21) are the constraints of the sales energy determination algorithm.

Equation (4) is the energy balance constraint, and (5) indicates that the state of charge(SOC) of the ESS is determined by the SOC of the previous time step and the ESS output power of the current time step. Equation (6) allows the final and initial SOCs of the ESS to be the same, and they can be set to the desired value. Equations (7) and (8) are constraints that limit the ESS output power below the rated output power. Equations (9) and (10) are constraints related to the quantity of trading with the main grid. Equations (11) through (21) are the upper and lower limits of the decision variables. Finally, to determine the prosumer's P2P trading energy, ESS optimal scheduling is carried out to simultaneously satisfy the above constraints, the demand of load consumption, and the demands from consumers.

C. DETERMINATION OF THE PURCHASE QUANTITY

As a follower of the game, the consumer decides his/her purchase quantity according to the sales price and quantity suggested by the prosumer. In this case, unlike the seller, the consumer does not own a DER such as a PV generator and ESS, but they can adjust his/her load consumption. Therefore, a part of his/her demand is satisfied through P2P trading, and the remaining energy is obtained from the main grid to satisfy his/her load consumption. The objective function and constraints of the purchase quantity determination algorithm of the consumer are as follows:

$$Max\left\{R_{i,t}\right\} = U_{i,t} - P_{i,t}^{P2P} \times \sum\nolimits_{j=1}^{S}\left(\lambda_{j,t} \times \alpha_{j,t}\right) - P_{i,t}^{grid,buy} \times \lambda_{up,t} \tag{22}$$

$$U_{i,t} = p_{i,t} \times \ln\left(P_{i,t}^{load} - P_{i,t}^{change}\right) - d_i \times P_{i,t}^{change^2} \tag{23}$$

$$\text{subject to } P_{i,t}^{change} + P_{i,t}^{grid,buy} + P_{i,t}^{P2P} = P_{i,t}^{load} \tag{24}$$

$$0 \leq P_{i,t}^{grid,buy} \leq P_{i,t}^{load} \tag{25}$$

$$-P_{i,t}^{load}/2 \leq P_{i,t}^{change} \leq P_{i,t}^{load}/2 \tag{26}$$

$$0 \leq P_{i,t}^{P2P} \leq P_{max}^{P2P} \tag{27}$$

Equation (22) estimates the purchase quantity required to maximize the utility function of individual buyers. In (23), it $U_{i,t}$ indicates the utility according to the load consumption. Here, a consumer who has a large utility parameter p_i will increase his/her load consumption to increase his/her utility. Conversely, a consumer who has a small utility parameter p_i will save on electricity bills by reducing his/her load consumption. In addition, the purchase quantity of the consumer is determined according to the discomfort parameter d_i for his/her load adjustment. The discomfort parameter for load adjustment is set differently for each consumer, similar to the utility parameter, and is the input data of the user. This considers the characteristics of the load consumption or load adjustment of the consumer.

Based on the above objectives and constraints, the individual consumers will calculate the hourly load adjustment, P2P trading quantity, and trading quantity from the main grid to maximize their revenue functions.

D. P2P PARTICIPATION RATIO UPDATE

After receiving the sales price and quantity information by the seller, Buyers determine a participation ratio in the trading. Through the trading participation ratio, sellers are allocated a certain percentage of the demand as their trading demand. Furthermore, the renewed trading demands of the sellers influence the pricing decision.

$$\alpha_{j,t} = \alpha_{j,t-1} + \sigma_1 \times P_{j,t}^{sell} \tag{28}$$

$$P_{j,t}^{req} = \alpha_{j,t} \times \sum\nolimits_{i=1}^{B} P_{i,t}^{P2P} \tag{29}$$

Equation (28) indicates that the prosumers' participation ratio is renewed according to the quantity of trading suggested by the prosumers. Here, $\alpha_{j,t}$ is the participation ratio of the buyer selecting a seller at time t, where $0 \leq \alpha_{j,t} \leq 1$, $\sum_{j=1}^{S} \alpha_{j,t} = 1$. According to the renewed participation ratio, the trading demand allocated to the prosumer is determined, as shown in (29). This acts as a requested demand from the prosumer's perspective, and in the next iteration, the price is renewed by comparing the quantity of demand with the surplus generated by the prosumer.

E. DETERMINATION OF THE DISTRIBUTION SYSTEM USAGE CHARGE (DSUC)

Most of the previous studies focused on developing an optimal bidding strategy to maximize the participants' trading profits. However, from the perspective of power system operators, the effect of a transaction on the system before and after P2P trading should be analyzed, to operate a stable system. The reason is that, if the prosumers who have profited from P2P trading connect renewable power sources to the distribution systems without any restrictions to increase their profits, network problems such as local overvoltage and reverse current may occur when power is generated. Therefore, in this study, a *DSUC* is charged for the voltage fluctuations generated through P2P trading.

$$\gamma_{base} = |1 - V_{base}| \tag{30}$$

$$\gamma_{P2P} = |1 - V_{P2P}| \tag{31}$$

$$\varphi_p = \varphi_{base} - (\gamma_{base} - \gamma_{P2P}) \times \varphi_{charge} \tag{32}$$

Equation (30) indicates the difference between the voltage of each bus and the reference voltage before P2P trading. Here, V_{base} represents the voltage of each bus before P2P trading. Equation (31) indicates the difference between the voltage of each bus and the reference voltage after P2P trading, where V_{P2P} represents the voltage of each bus after P2P trading. After the aforementioned differences are derived, the *DSUC* charged to the prosumer is calculated according to the difference in voltage fluctuation before and after P2P trading, as shown in Equation (32). Here, γ_{base} is the basic rate of *DSUC* and is calculated as 20% of the trading revenue. φ_{charge} is this value multiplied by the voltage fluctuation. The charge charged according to the degree of contribution to the voltage stability through P2P transactions is calculated by calculating the *DSUC* according to the magnitude of voltage fluctuation of the corresponding bus.

III. CASE STUDY

In this section, three cases are reviewed to verify the performance of the proposed P2P trading algorithm. The prosumers assume that they can sell their surplus power via the main grid and through P2P trading. All the case studies assumed that there were three prosumers and 15 consumers in the community. Figure 3 shows the consumer load profile.

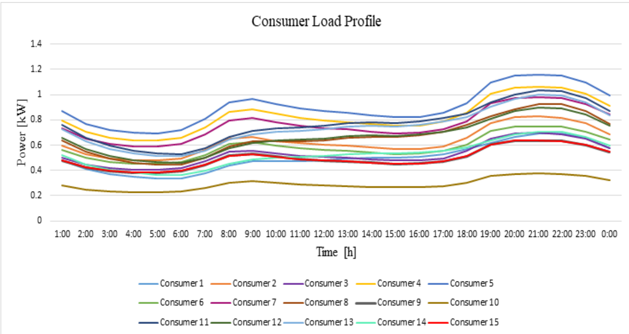

FIGURE 3. Consumer load profile.

All the participants in the trading were assumed to follow the household load consumption pattern which generated by using the working day(Monday-Friday) data of 2018 Korea Electric Power Research Institute's analysis of power consumption behavior [20], and the prosumers participating in P2P trading assumed that they could control the DERs owned by the ESS together with the small-scale PV devices. It is assumed that the prosumers own solar generators of different rated capacities, i.e., 3 [kW], 6 [kW], and 9 [kW]. They also have an installed battery of capacity 15 kWh. The charging and discharging efficiencies are considered as 90%. Moreover, the charging and discharging power are assumed to be 5 [kW].

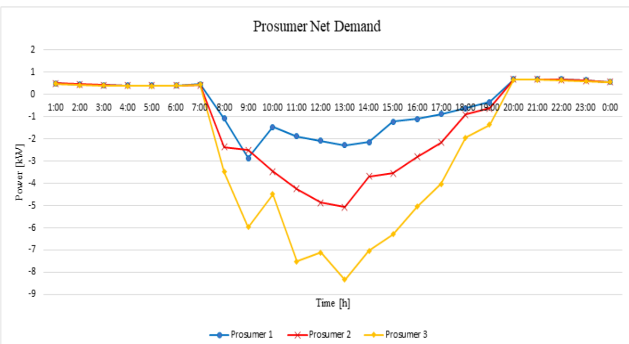

FIGURE 4. Prosumer net demand.

The test system for analyzing the impact of P2P trading is assumed to be an 18-bus radial distribution system, and the system configuration is shown in Figure 5. In addition, the system parameters applied to the test system are shown in Table 1. In the test system, it was assumed that the prosumers exist on buses 11, 13, and 18.

In this study, we compare and analyze the prosumer's revenue and power flow when conducting P2P trading in three cases. Table 2 shows the case study configurations. Case A

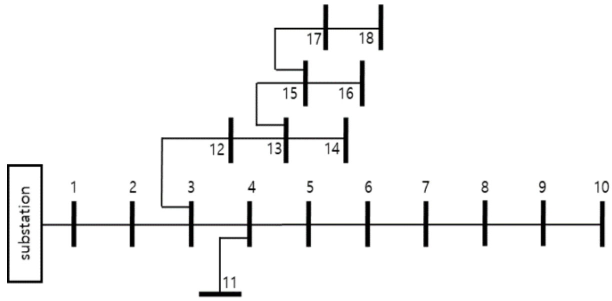

FIGURE 5. 18-bus radial distribution test system [21].

TABLE 1. 18-bus branch data.

From	To	R(p.u.)	X(p.u.)	b(p.u.)
1	2	0.00004998	0.00035398	0.00000000
2	3	0.00031200	0.00675302	0.00000000
3	4	0.00043098	0.00120403	0.00035000
4	5	0.00060102	0.00167699	0.00049000
5	6	0.00031603	0.00088198	0.00026000
6	7	0.00089600	0.00250202	0.00073000
7	8	0.00029498	0.00082400	0.00024000
8	9	0.00172000	0.00212000	0.00046000
9	10	0.00407002	0.00305299	0.00051000
4	11	0.00170598	0.00220902	0.00043000
3	12	0.00291002	0.00376800	000074000
12	13	0.00222202	0.00287699	0.00056000
13	14	0.00480301	0.00621798	0.00122000
13	15	0.00398502	0.00516000	0.00101000
15	16	0.00291002	0.00376800	0.00074000
15	17	0.00372698	0.00459302	0.00100000
17	18	0.00110400	0.00136000	0.00118000

TABLE 2. Case classification.

Case	Trading Price	Demand Control	ESS
A	$\lambda_{low,t}$	X	X
B	$\lambda_{j,t}$	O	X
C	$\lambda_{j,t}$	O	O

is an example in which the prosumers do not participate in P2P trading. In this case, the prosumer's surplus power is sold to the main grid, and the selling price is assumed to be the system marginal price(SMP). Case B is an example in which the prosumers who actively control their demand participate in P2P trading. Case C is an example of prosumers participating in P2P trading by adjusting their demands and owning an ESS and actively adjusting their surplus power generation.

A. SIMULATION RESULTS

Case A is a scenario in which P2P trading is not undertaken, and the prosumers sell their surplus power to the main grid. Therefore, a prosumer's profit by selling surplus power to the main grid is calculated as Equation (33).

$$P_{j,t}^{exc} \times \lambda_{low,t} \tag{33}$$

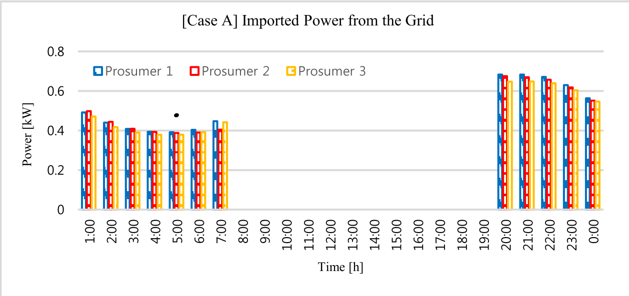

FIGURE 6. Total power imported from the grid [Case A].

Figure 6 shows the quantity of power purchased by the prosumers from the main grid in Case A. The prosumers satisfy their load consumption by purchasing power from the main grid during times when no power is generated (01:00–07:00; 20:00–24:00). Figure 7 shows the quantity of power sold by the prosumers via the main grid in Case A.

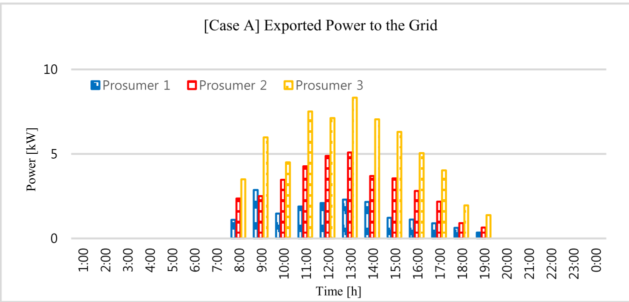

FIGURE 7. Total power exported to the grid [Case A].

It can be observed that the greater the surplus power generated by the prosumers, the more power they sell via the main grid. When the power is solely traded with the system as in Case A, the possibility of reverse flow during power generation increases as more renewable energy sources are connected to the low-voltage distribution system, which causes an overvoltage in each part of the low-voltage distribution line.

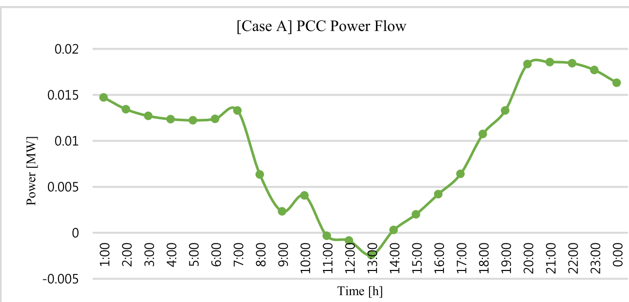

FIGURE 8. PCC power flow [Case A].

In Case B, the prosumers participate in P2P trading through load adjustment. In this case, the prosumer adjusts his/her trading quantity by increasing or decreasing his/her load consumption according to the utility of the load usage. P2P trading was assumed to occur at the time of surplus power generation. Figure 10 shows the P2P trading price offered by the prosumers. It can be confirmed that the P2P trading price

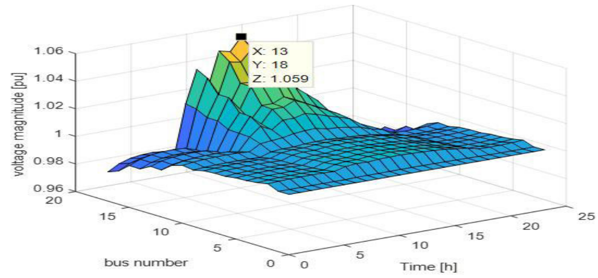

FIGURE 9. Bus voltage [Case A].

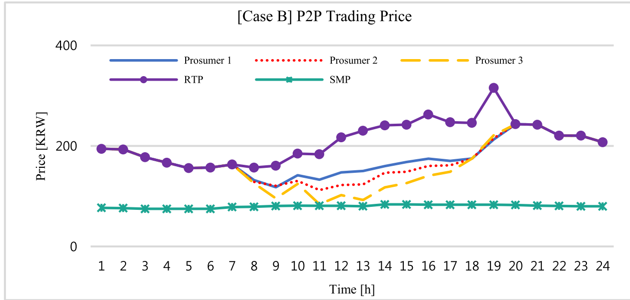

FIGURE 10. P2P trading price [Case B].

coincides with the system purchase price in the absence of power generation. At other times, as the prosumers' surplus power increases, they increase their P2P trading quantity by lowering their trading price from the system purchase price. Therefore, the trading price of Prosumer 3, who generated the highest surplus power, is the lowest.

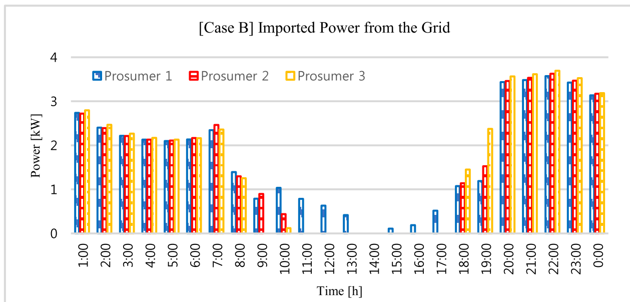

FIGURE 11. Total power imported from the grid [Case B].

Figure 11 shows the quantity of power purchased by the prosumers from the main grid to satisfy their load usage and the buyers' P2P trading demand. Figure 12 shows that the prosumer sells the surplus power, after satisfying both load consumption and P2P trading demand, to the main grid. Prosumer 3 generated the highest surplus power, and hence, also sold the highest quantity of power to the main grid.

However, compared with Case A in which all the surplus power was sold to the main grid, the quantity of power sold to the main grid has been significantly reduced in case B. Thus, from the prosumer's point of view, surplus power was sold at a higher price through P2P trading than through the grid ($\lambda_{low,t}$).

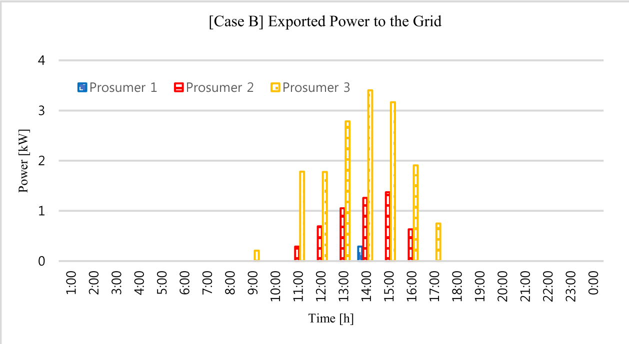

FIGURE 12. **Total power exported to the grid [Case B].**

In Case C, the prosumers participate in P2P trading through ESS operation and load adjustment. Unlike in the other cases, the prosumer owns the ESS, and hence, P2P trading is possible even when no power is generated. The price for P2P trading proposed by the prosumer in Case C is shown in Figure 16.

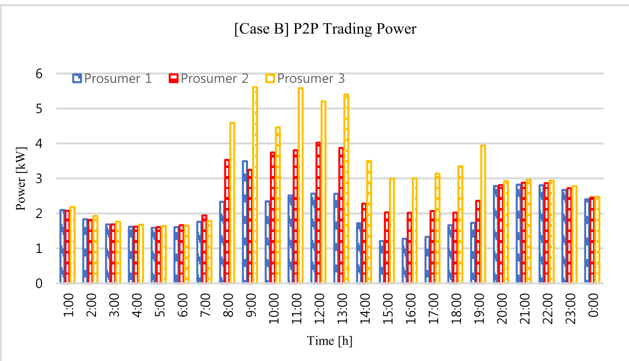

FIGURE 13. **P2P trading power [Case B].**

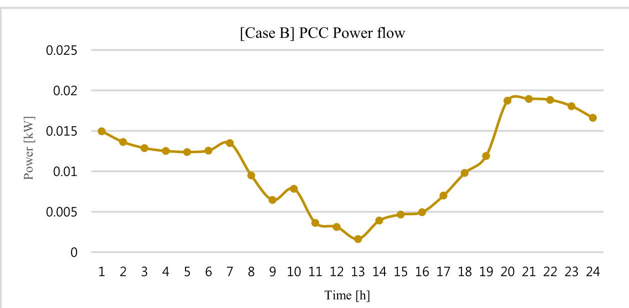

FIGURE 14. **PCC power flow [Case B].**

When no power is generated, the demand is greater than the supply; hence, the trading price is almost equal to the price of the purchase from the main grid ($\lambda_{up,t}$).

However, as the surplus generated by the prosumers increases, their strategy is to increase the sales volume by lowering the price from 8 A.M. to 7 P.M. compared with the price of the purchase from the main grid. Therefore, Prosumer 3, who generates the highest surplus power, offers the lowest trading price compared with the other prosumers. In addition, surplus power is charged through ESS scheduling in Case C,

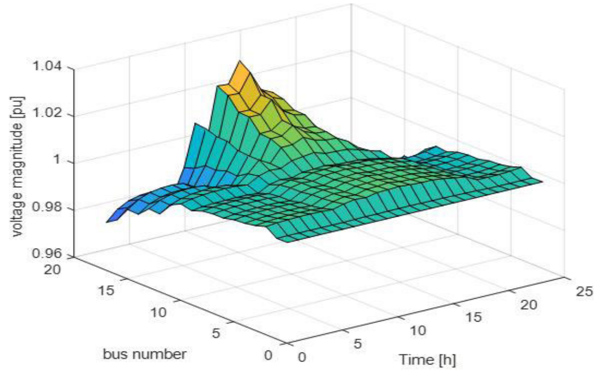

FIGURE 15. **Bus voltage [Case B].**

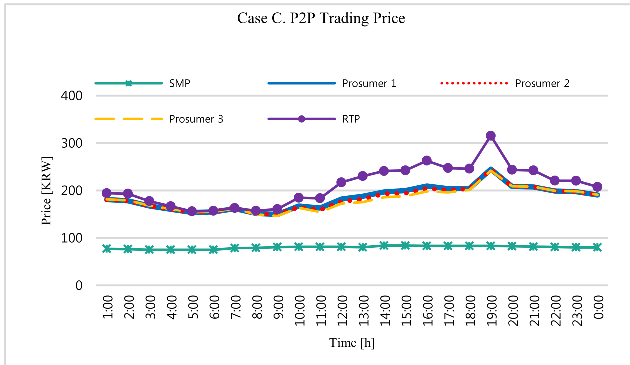

FIGURE 16. **P2P trading price [Case C].**

and it is possible to trade power through discharge even when no power is generated. Therefore, the sales price is higher than in Case B, where it is advantageous to sell as much as possible when power is generated.

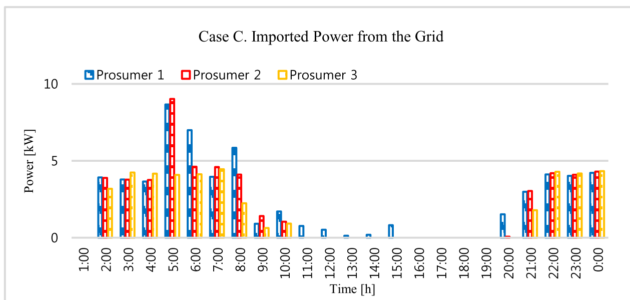

FIGURE 17. **Total power imported from the grid [Case C].**

Figure 17 shows the quantity of power purchased by the prosumers from the main grid to satisfy their load usage and the demand for P2P trading. It is mainly purchased at times when no power is generated, and the lowest purchase price from the main grid is observed at 5:00 A.M.

Figure 18 shows the power sales of the prosumers via the main grid. This refers to the quantity of power remaining, upon excluding the demand for P2P trading and the real-time load usage of the prosumers from the surplus power generated. Prosumers 1 and 2 have no surplus power after P2P trading; hence, no power remains to be sold to the main

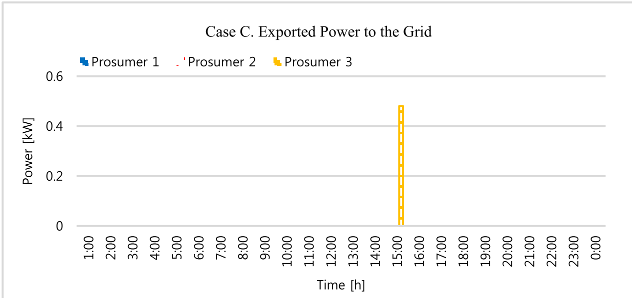

FIGURE 18. Total power exported to the grid [Case C].

grid, whereas Prosumer 3 sells power to the system at 3 P.M. However, compared with the previous cases, the quantity of power sold to the main grid has been significantly reduced. This indicates that the surplus power of the prosumers was used mostly for P2P trading.

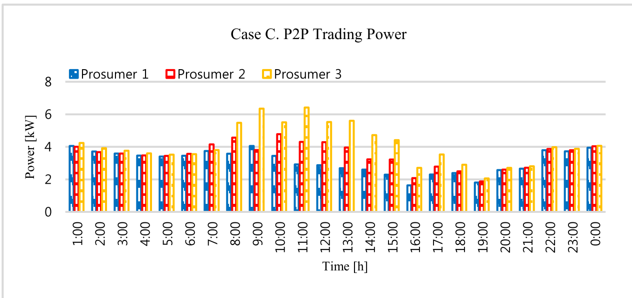

FIGURE 19. P2P trading power [Case C].

Figure 19 shows the P2P trading volume of the prosumers. In Case C, the quantity of P2P trading increased compared with that in Case B because the prosumers participated in the trading through ESS operation and load adjustment. In addition, the sales volume exists even when there is no surplus power generation through ESS operation. Similar to Case B, the quantity of power traded by the prosumers is determined through game theory in this case as well; therefore, it can be confirmed that Prosumer 3, who had the lowest trading price, possessed the highest trading participation rate, and thus, the highest trading volume.

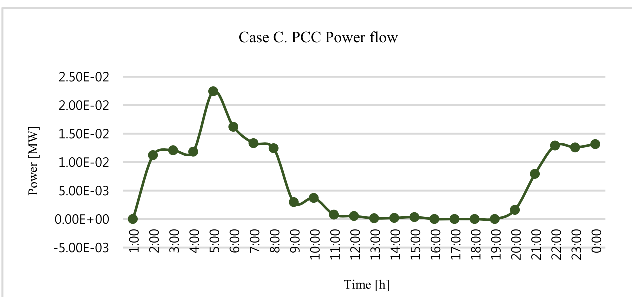

FIGURE 20. PCC power flow [Case C].

Figure 20 shows the power flow of the PCC of the distribution system to which the prosumer belongs in Case C.

In contrast with Case A, the reverse flow from PCC disappeared in this case, and in contrast with Case B, the power flow when there was surplus power was reduced. This is because the demand generated in the distribution system was satisfied through P2P power trading.

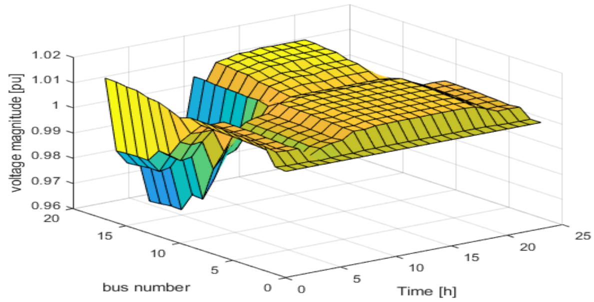

FIGURE 21. Bus voltage [Case C].

Figure 21 shows the bus voltage over time for Case C. In Case A, the upper limit of the maintenance reference voltage exceeded 1.05 [p.u.] in bus 18, to which Prosumer 3 belongs; however, in Case C, the voltage at all times for all the buses was maintained in the range of 0.95 [p.u.] to 1.05 [p.u.] through ESS operation with load adjustment for P2P trading.

B. DISTRIBUTION SYSTEM USAGE CHARGE

The comprehensive results obtained via system analysis confirmed that the quantity of power received from the main grid decreased through the prosumer's P2P trading, and the reverse power flow disappeared, which could have a positive effect on the power system.

This is because the P2P trading price suggested by the prosumer was lower than $\lambda_{up,t}$; consequently, the consumers prioritized P2P trading, and the prosumer could also sell at a price higher than $\lambda_{low,t}$. However, as P2P trading was activated, the revenue of the utility company decreased. In addition, the P2P trading did not use a dedicated line, but used the existing distribution system; hence, it is necessary to consider the *DSUC* in P2P trading.

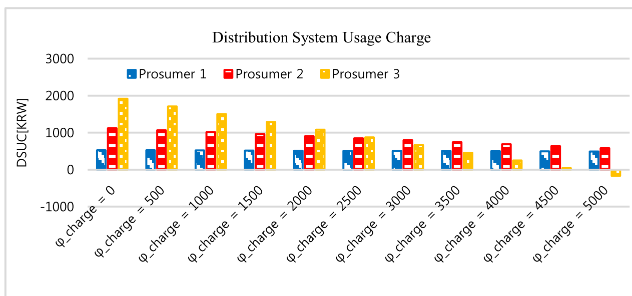

FIGURE 22. Distribution system usage charge.

Figure 22 shows the DSUC charged to the prosumers when the *DSUCs* are calculated according to the difference obtained from the reference voltage, as shown in Equation (32). The base charge(φ_{Base}) was calculated as 20% of the P2P trading revenue. This allowed the prosumers with high trading revenues to pay more. In addition, the charge for voltage fluctuation (φ_{charge}) was increased by 500 KRW from 500 KRW to 5,000 KRW, and it is calculated as the point at which the increase and decrease rates of the DSO and the prosumer, respectively, cross. As shown in Figure 22, the *DSUC* that must be paid by the prosumer decreases as φ_{charge} increases, because the voltage has stabilized after P2P trading compared with that before P2P trading. Therefore, as φ_{charge} increases, the *DSUC* of the prosumer decreases linearly. Furthermore, when φ_{charge} becomes greater than 5,500 KRW, the *DSUC* of Prosumer 3 has a negative value. The reason is that, Prosumer 3, who is the farthest from the system, contributed the most to reducing the corresponding bus's voltage fluctuation through P2P trading.

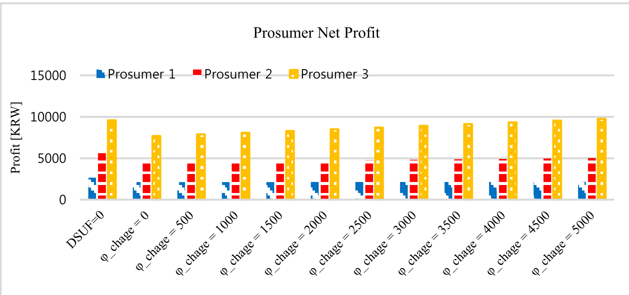

FIGURE 23. Profit analysis of prosumer.

Figure 23 shows the profits that can be gained from trading when the *DSUC* is included. As explained earlier, as the voltage stability has improved due to P2P trading by the prosumers, the *DSUC* that must be paid by the prosumers decreases as φ_{charge} increases. Therefore, the larger the φ_{charge}, the higher is the profit of the prosumers. Proper *DSUC* calculation is important to consider the economic operation of the utility company along with prosumer profits.

In this study, we derived the price at which the prosumer's net profit growth rate and the decrease rate of *DSUC* intersect with the increase in φ_{charge} as an appropriate φ_{charge} value.

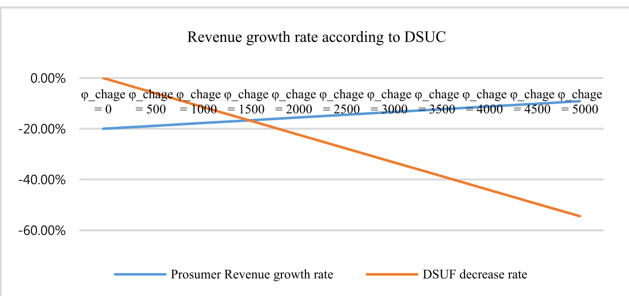

FIGURE 24. Revenue growth rate according to DSUC.

Figure 24 shows the change in the prosumer revenue growth rate and the decrease rate of *DSUC* with a change in φ_{charge}. If the decrease rate of *DSUC* is high, a smaller φ_{charge} is selected; thus, the *DSUC* will increase. In the opposite case, assuming that the prosumer revenue growth rate is substantially modest, φ_{charge} will cross at a higher point, increasing the *DSUC* that must be paid by the prosumer. In the present case, it was confirmed that φ_{charge} crosses at 1,500 KRW, and approximately 15% of the P2P trading revenue is paid as the *DSUC*.

IV. CONCLUSION

In this paper, we proposed a P2P trading algorithm for trading between prosumers and consumers based on the Stackelberg game theory. The proposed algorithm includes the seller's strategy algorithm and the buyer's strategy algorithm. Here, the seller's strategy is the sales price and quantity, and the buyer's strategy is to update the participation ratio. Three case studies were conducted to verify the performance of the proposed algorithm. In each case, the amount of P2P trading was changed according to the trading strategy suggested by the participants, and a power flow analysis was performed in each case. Based on the power flow analysis, we proposed a method to charge DSUC to prosumers to alleviate the burden on the utility company caused by P2P power trading. The *DSUC* was calculated based on the additionally analyzed voltage for each bus, and the profit guarantee of the utility company was also considered. Consequently, by comparing the voltage fluctuations before and after P2P trading and charging a charge, a method was proposed to reduce the charge for the prosumers who positively influenced the system operation through P2P trading. The appropriate *DSUC* is expected to act as an inducement for utility companies to allow P2P trading in countries like Korea, which have a monopolistic structure.

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