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Competition and Coalition of the Participants with Demand Response in Electricity Market

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Abstract – This study deals with the design of the mechanism in which demand response (DR) resources are traded in the power generation market. In general, a DR aggregator (DRA), which extends DR resources and provides technical support, is central to this mechanism. In this study, power users, called DR customer (DRC), participate in load reduction and are also modeled to participate directly in DR-related bidding. The DRA provides incentives to the DRC, indirectly impacting the market, and the DRC use the bid parameters strategically. We present the conditions for finding Nash Equilibrium (NE) in game problems of various participants including market operators, and analyze the characteristics of DRA and DRC related models. It also analyzes the impact of the participants on the market according to various types of competition and coalitions between DRA and DRC.

Keywords: Demand response, Demand response aggregator, Competition and coalition, Load reduction, Nash equilibrium

1. Introduction

Power consumption in the Republic of Korea has increased at an average annual rate of 4.1% over the past decade. Due to the difficulties in securing domestic and foreign energy resources and the increase in social costs in nuclear power generation facilities, it is necessary to shift to a previous approach that depends only on power generation facilities. In accordance with this demand, the direction of energy policy is shifting from supply side to demand side management in various countries. The government of the Republic of Korea aims to increase the capacity of demand resources to 3% of electricity demand [1]. Demand Response (DR) is the capacity to reduce power consumption voluntarily. By utilizing demand resources at peak load, it is possible to avoid high power generation cost and expect stable power supply [2,3]. In addition, the introduction of DR will increase the price elasticity of electric power demand [4], and market power can be expected to be mitigated in the electricity market. For example, California's energy crisis at the turn of the millennium could, to a large extent, have been mitigated if sufficient DR was in place [5].

Several advantages of DR are discussed, but the important point is that the load to participate in DR is sufficiently secured and stable. To do this, DR must be valued accurately in the electricity market. In this study, we focus on the regulation of DR market, roles and strategies of DR market participants so that DR pricing can be linked with the power generation market. In the domestic electric power market, the DRA performs tasks such as registration of demand resources, verification of reliability, and receives monitoring and demand reduction instruction from the market operator (MO). Meanwhile, the DRA conducts tasks such as inducing power users to participate in the electricity market, installing monitoring and energy management systems, and instructing demand reduction [6].

A study focusing on the role of DRA [7,8] studied the strategic choice of DRA with the Stackelberg model after setting the DRA as an intermediary coordinator for load reductions between MO and DR customers (DRC). Another study on the role of DRA [9] also dealt with the relationship between MO and end-users as a hierarchical structure. In addition, in [10], DRA reflects the cost of load reductions on behalf of the DRC, and argues that the market price is reduced by finding the Nash Equilibrium by applying the Cournot model for generation competition. Nguyen [11] analyzed the efficiency of purchasing DR and contribution rates of DR by buyers as transmission system operator, distribution companies, and retailers. Chen [12] and Lee[13] dealt with the game problem of the bidding function by assuming DRA as a strategic participating model. On the other hand, [14] defined the reduction purchase curves and studied the behavior of purchase competition of load reduction among the loads in the DR market combined with the generation power market.

In DR market modeling [6~9], the function of DRA is emphasized and highlighted, while the role of customers participating in DR is considered relatively less. DRC's willingness is reflected to the extent that it negotiates with the DRA about the cost of the reduction. However, in the recent development of the smart grid technology, DRC may directly participate in the bidding of the market.

In this study, DRC is modeled by strategically bidding load reduction while considering the reduction cost of

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DRC itself. On the other hand, the DRA is modeled by indirectly affecting DRC's bidding using incentives for load reduction. This study defines the objective function of market participants (DRA, DRC) including market operators and presents optimal conditions for calculating the Nash Equilibrium for the market clearing price. The impact of DR on the market is defined as the reduction of market price, and the characteristics of various parameters presented in this study are analyzed. In particular, we analyze competition and coalition of various combinations of DRC and DRA, and their market outcomes. The combination of competition and coalition results in a complicated situation, and the priorities of several factors affecting the market are presented by numerous case studies.

2. Modeling of DR Participants

2.1 Generation market and DR market

The purpose of DR is to induce the load reduction to lower the generation cost when the marginal cost rises to a higher demand load. Therefore, the economic effect of DR is closely related to market price or marginal cost in the generation market. To reflect this, the generation market and the DR market should be integrated. If the marginal cost in the power generation market is high, the market should be designed so that the willingness to participate in the DR market will increase. Also, if the load reduction as DR resources increases, the marginal cost of generation will be lowered and the corresponding payoff must be given to DR participants.

In this study, the integrated market is modeled with the structure that the market operator determines the price of DR and the generation power by linking the DR market with the electricity market. In order to participate in DR, the electricity customers need facilities and technical support as well as willingness to participate. This service is provided by DRA (DR aggregator). In this study, we model that DRA makes an incentive payment to DRC for the load reduction in order to recruit DR resources. In other words, DRA maximizes its profit by using a strategy variable called incentive. The participation of DRC in electricity market is also modeled as a strategic choice. The DRC is modeled as a bidder to the market operator in the form of a supply function for load reduction, taking into account the cost of reducing the load.

2.2 Participants' interrelation

In order to analyze the integrated market of power generation and DR resource, the items to be submitted or decided by each participant are defined as shown in the following Fig. 1. In the figure, the left is the power generation market and the right is the DR market. The MO balances demand and supply based on demand function (*DF*) and supply function (*SF*), and performs market clearing for power generation, load reduction and price. Generation companies (Genco) are designated as price-takers, so they do not exercise market power. This places the focus on the model and behavior of DR participants.

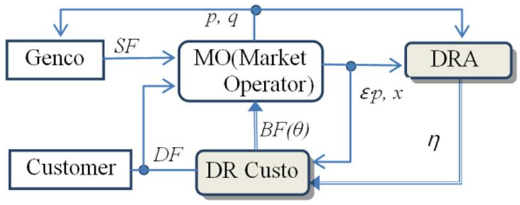

Fig. 1. Interrelation of integrated market and participants

Among the power customers in Fig.1, the lower left is a customer that does not participate in DR, while the other (shaded) is a customer that participates in DR through a contract with a DRA, and consumes load power. The DRC is willing to reduce its load power according to the incentive (η) proposed by the contractor DRA. This commitment is reflected in the bid parameters (θ) of DRC and submitted to the MO.

The DRA's payoff is proportional to the load reduction (x) and price (p). While prices are affected by the electricity market, reductions are influenced by the bidding of its contracted customer DRC with a bidding function (*BF*). The greater the incentive of the DRA, the higher the willingness of the DRC to reduce load power. As a result, the DRA's benefit depends on its own strategy (η). Therefore, it can be expected that the effect of DRA's profit maximization will increase the scale of DR resources.

2.3 Strategy of DRC

In the past, power consumers have only been in the demand side of the electricity market paying for the use of electricity. However, by introducing the DR system, which recognizes the reduction of electricity use as a resource, the consumers can now also serve as a supply in the market.

The demand side of the DRC follows the usual method by the demand function, and the modeling of supply side of DR is described in detail. Basically, the amount of load reduction is determined by the MO in the market through DRC's participation in the bidding. The market clearing load reduction is made by a supply function model, which is one of the well-used models for analyzing the power generation market [15]. The strategic supply function is defined as a linear function as in Fig. 2. Theta in Fig. 2 functions as a strategic variable indicating the willingness to reduce its load. This bid function is corresponding to *BF* in Fig. 1. Theta is a value between 0 and 1, and the closer to 1 (higher willingness), the lower the intercept of the function, so the amount of reduction will be determined to a large extent.

When DRC bids, it considers maximization of profit by

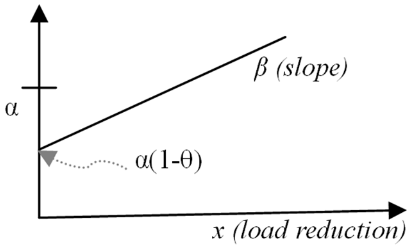

Fig. 2. Bid function for load reduction

load reduction. The profit of DRC is the sum of a monetary reward for the reduction and the cost of the reduction as (1). In the equation, x_{jk} represents the reduction load, subscripts j and k represent the k-th DRC contracted with the j-th DRA. A market price of generation power p, and η_j represents the incentive proposed by DRA_j. How to calculate the price of DR and generation power in the integrated market is very important. In this study, the parameter ε is defined as the ratio of the DR price to the generation power price, and it can be controlled by MO. Thus, in the first term in (1), the revenue for the reduction load is defined by the combined price from the MO (p) and the incentive from the DRA (η_j). $C_d(x_{jk})$ represents the cost due to the load reduction.

$$max_{\theta_{jk}}\{\pi_{jk}^c = (\epsilon\cdot p + \eta_j)x_{jk} - C_d(x_{jk})\} \quad (1)$$

In the proposed DRC profit equation, the bid parameter of DRC, θ, does not appear in (1), but the parameter can affect the market clearing of price and load reduction. The optimal parameter to maximize the DRC profit can be obtained by solving the equation $\frac{\partial \pi_{jk}^c}{\partial \theta_{jk}} = 0$

2.4 Objective of DRA

DRA plays an important role in that DRC participates in the market voluntarily, DR is traded economically and load reduction is implemented technically. In this study, we try to model the relationship between the voluntary participation and the economic transaction closely related to the electricity market. Since the supplier of the DR is the DRC, the decreased payment by consumer to MO is reasonably paid to the DRC as shown in (1) as product of the load reduction and the market price

Then how is the reward given to the DRA for acting as the intermediate role appropriate? The DR is a kind of emergency resource that works when there is an urgent need for power in the electricity market. In this study, we define the expected financial effect of the DR implementation to be paid to the DRA. This can be expressed as (2).

$$max_{\eta_j}\{\pi_j^A = \sum_k p_0 d_{0jk} - \sum_k \epsilon\cdot p\cdot(d_{jk}-x_{jk}) - \eta_j\cdot\sum_k x_{jk}\} \quad (2)$$

where, p is the market price, d is the load power allocated by the demand function, and x is the load reduction. Thus d-x is the actual load power used at the jk load.

The DRA's profit of (2) consists of three components related to the amount paid to DRA_j and the cost that DRA_j pays. The first term is the amount required to pay for the load jk when the DR is not enforced, and the second term is the amount that must be paid for the load when the DR is implemented. The difference between the two is paid to the DRA_j as income. In other words, the market will give back to the DRA a reduced charge. There may be controversy about the legitimacy, or rationality, of actually paying the virtual savings that did not occur. However, it should not be underestimated that the fundamental starting point of the DR system is to limit the temporary surge in power generation costs, thereby reducing power generation and facility costs. The third term is an incentive payment that DRA must pay to a customer DRC with whom there is a contract. In order to reduce costs of DRA in (2), lowering the incentive parameter η reduces the DRC's profit as shown in (1), so that the DRC will passively bid for the reduction, resulting in a decrease in the load reduction, and thus a reduction in the revenue of DRA_j. Therefore, DRA_j will try to find its strategic incentive to maximize the profit, and the optimal parameter is obtained by solving the condition $\frac{\partial \pi_j^A}{\partial \eta_j} = 0$.

2.5 Function of MO

Market Operator plays a key role in the power and DR market. It is necessary to balance the demand and supply and to satisfy the economic effect and rationality of the public interest. Although not discussed in this study, the physical limitations of power generation and transmission facilities must be considered. The DR market needs to be integrated with the existing generation market, so the role and responsibility of MO become more complex and important.

In the microeconomic analysis of the electricity market, the objective of MO is generally defined as Social Welfare. The expanded SW that is modified considering the DR market in the conventional SW concept is shown in (3).

$$max\ \{SW = \sum_i B(d_i) - \sum_n C(q_n) - \sum_j\sum_k W(x_{jk})\} \quad (3.1)$$

$$\text{s.t. } \sum_i d_i = \sum_n q_n + \sum_j\sum_k x_{jk} \quad (3.2)$$

$$\text{where } B(d_i) = \int_0^{d_i}(DF)_i\,dz \quad (3.3)$$

$$C(q_n) = \int_0^{q_n}(SF)_n\,dz \quad (3.4)$$

$$W(x_{jk}) = \int_0^{x_{jk}}(BF)_{jk}\,dz \quad (3.5)$$

In the three terms of SW, the first and second terms are the same as in the conventional definition. That is, $B(d_i)$ with demand d_i represents benefit obtained by integrating the demand function (DF) and $C(q_n)$ where the power generation cost is obtained by integrating the supply function (SF). The third term is a reduction cost calculated by the reduction bidding function (BF) proposed by DRC. $W(x)$ with load reduction x here is different from the cost C_d in (1) which is the actual cost due to the reduction of DRC, and $W(x)$ contains the strategic choice (θ) of DRC.

The load reduction should also be considered in balancing the power in the electricity market. Since the demand d_i is a load calculated from the demand function (DF) irrespective of the DR, it is equal to the sum of the power generation (q) and the load reduction (x) as in (3.2). The inclusion of the actual power cost function in the SW as in (3.1) implies that the generation power competition is treated as a perfect competition model. As mentioned above, the MO should perform market-clearing of the market price, demand quantity, and reduction quantity by maximizing the modified SW. In addition to this market clearing, this model allows the MO to define the DR price coefficient parameter (ε), which represents the ratio of the DR price to the power generation price.

3. Parameters in DR Market

3.1 Equilibrium of the participants competition

DRAs and DRCs in the DR market, including the MO, will pursue strategic choices to maximize their own objectives, and their options are directly or indirectly influenced by each other. The DRA incentive variable (η) affects indirectly the integrated market through DRC, but DRC has a direct impact on the integrated market through the ability to bid. The reduction load (x) from market clearing also affects the choice of DRA and DRC. The convergence state of each choice can be defined as Nash Equilibrium (NE). The NE state corresponds to a solution satisfying the optimal conditions of the objective function of each participant.

To illustrate the results of applying the DR participant model presented in this study, we use the sample systems as shown in Fig. 3. The system includes participants of MO, DRA and DRC, one each. Since a generation competition is assumed to be under perfect competition, only one generation is enough to reflect the competitive nature of the power source. The entire load participates in the DR with a single DRA, and this form is referred to as a reference in the following studies in this paper.

Table 1 shows the numerical data of the participants in

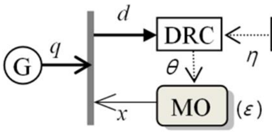

Fig. 3 Sample system and market participation

Table 1. Numeric data of parameters of market participants

Parameters	Supply Function (SF)	Demand Function (DF)	Bid Function (BF)	Cost Function (C_d)	price factor for DR
Expression	$b + m\,q$	$a - r\,d$	$\alpha\,(1-\theta) + \beta\,x$	$0.5\,\gamma\,x^2$	$\varepsilon\,p$
Numerical data	b=0, m=0.2	a=200, r=0.8	α=40, β=1.0	γ=2.5	ε=1.0

Table 2. Market results of the sample system

NE	Market Price (p)	Generation Power (q)	Demand Power (d)	Demand Reduction (x)	Bid Parameter of DRC (θ)	Incentive of DRA (η)
w/o DR	40	200	200	0	-	-
w/ DR	37.18	185.89	203.53	17.64	0.512	9.742

the sample integrated market. The supply function is the marginal cost function of the generator and the demand function is the demand characteristic represented by a single load. The bidding function, reduction cost function for DRC, and the price factor of DR are also included.

In the bid function for load reduction, the slope of the function is set to β, the maximum value of the intercept is set to α, and the cost function for reduction is defined as a quadratic function with coefficient γ. In addition, the price correction factor (ε) for DR is set at 1.0, which means that the prices of power generation and the DR are equally valuated as 1:1. The NE state is calculated by reflecting the DR market, DRC, and DRA. The results are shown in Table 2.

The market clearing state without DR market is obtained at the intersection of the demand-supply function graph. The result is p=40, q=d=200. As DR market works and all participants have a reasonable and optimal choice. In the NE, DRC tries to bid with θ=0.512 and DRA offers η=9.742 as incentive. The load reduction is 17.64, so the power generation decreases to 185.89 and the market price decreases to 37.18. Compared with the state without DR, the power generation decreased by about 7.1% (=(200-186)/200). The price of the DR is the same as the generation power due to ε=1.0, but the price at which DRC is paid, increases to 46.92 due to the incentive added as in (1).

3.2 Price correction factor of DR

Pricing for DR resource is a very important in securing DR sufficiently. Higher pricing will increase DR, and lower pricing will decrease DR. By introducing the correction factor parameter (ε) of the DR price against the generation power price, the result of the variation in price setting can be analyzed. Table 3 below compares the results of increasing and decreasing the correction factor.

As the correction factor (ε) increases in Table 3, the valuation for DR increases, so the willingness to reduce increases and the load reduction (x) increases as well. As a result, the market price and the power generation decline.

Table 3. Market results with the different price coefficient

Price factor	p	q	d	x	θ	η	$\varepsilon \cdot p$+ η
ε=0.9	37.26	186.28	203.43	17.15	0.394	11.805	45.344
ε=1.0	37.18	185.89	203.53	17.64	0.512	9.742	46.922
ε=1.1	37.10	185.50	203.62	18.12	0.610	7.681	48.491

Table 4. Comparison with and without incentive from DRA

Incentive	p	q	D	x	θ	π^A	π^C
η=0	37.73	188.65	202.84	14.18	0.411	882.05	283.69
η=9.74	37.18	185.89	203.53	17.64	0.512	917.23	438.70

Interestingly, DRA incentives (η) are rather reduced. It can be understood that the effect of incentive is relatively reduced when the valuation of DR increases in the market. Though the incentive is reduced, the unit cost of the payment to DRC is increased by ε·p+η, from 45.3 to 48.5, as the correction factor increases.

3.3 Incentive of DRA

In addition to the way in which DR resources are traded at a price comparable to power generation, this study proposes DRA incentives. The method of DR pricing dependent only on the voluntary willingness of DRC is seemingly not an effective tool for revitalizing the DR market. The incentive payment to DRC from DRA is expected to make DR amount bigger. The following Table 4 shows the result of comparing the NE state with incentive and without incentive (η=0). The incentive value (η=9.74) is referred to Table 2. The price correction factor (ε) of DR is set to 1.0.

In Table 4, the introduction of the incentive system shows that the load reduction of DRC increases from 14.18 to 17.64, and the market price decreases. In addition, the DRA and DRC profits (π^A, π^C) show that the DRA increases its profits from 882 to 917, despite payment of an incentive to the DRC. This is seen as a positive result of the incentive system.

4. Competition of DRC and DRA

4.1 Non-DR customer (NRC)

As a reference for comparative studies in this paper, the model in which the entire electricity consumer participates in the DR with contracting with a single DRA is addressed in Section 3.1. However, it is very rare for the entire load to participate in the DR market. It is common for less electricity users to participate in the DR and for more users not to. We call this user a non-DR customer (NRC), and consider what happens to a NRC when the DR market works.

The demand function is divided into NRC and DRC contracted with a single DRA, while keeping the overall demand function the same as in section 3.1. The numerical data for the market and the participants are the same as in Table 1. We divide the load into D_1 and D_2 and define each demand function as 200-1.2d_1 and 200-2.4d_2. When two demand functions are added up, it corresponds to 200-0.8d in Table 1. Among the two loads, D_1 is not involved, D_2 is contracted with DRA to participate in DR. Then the NE state is calculated as follows in Table 5. The price correction factor of DR is 1.0 and the result is compared with the situation where the DR market does not operate.

Table 5. Comparative results of DR and non-DR demand

DR type	p	q	d_1	d_2	x_2	θ_2	η
w/o DR	40	200	133.33	66.67	0	-	-
DRC+NRC	37.63	188.15	135.31	67.65	14.82	0.430	1.787

The DR load decreases to about 1/3 (=66/200) as compared with the DR load in the reference, since the slope of the demand function of D_1 is half to that of D_2. Therefore, the reduction amount (x) decreases to 14.82 from 17.64, and the bid parameter (ε) of D_2 and the incentive of the DRA decrease. The load power of NRC is 135.31 and the load power of the DRC is 52.83 (= 67.65-14.82). On the other hand, when the DR market is not working, the load powers are 133.33 (d_{01}) and 66.67 (d_{02}), when the DR market is operated, the load power of the DRC greatly decreases, while NRC increases.

Note here that D_1, the NRC load, consumes more power (133.33 -> 135.31) at lower prices (40 -> 37.63) than when the DR market is not working. It can be considered a free rider problem [17] because it receives benefits from DR without participating in DR. However, this result can be interpreted as positive in that the DRC gain more than NRC and the benefit from DR is distributed to everyone participating in the electricity market.

4.2 Competition between DRCs

From the previous case, we change some setting on the loads. The NRC participates in the DR market through the DRA. In other words, NRC becomes a DRC in this case. Qualitative results can be easily predicted because loads with larger demand power participate in DR. That is, reductions will increase and market prices will decrease further. In the sense that the total load is involved in the DR market and there is one DRA, it is the same as the reference case in Section 3.1. However, if the DRC, D_1 and D_2, are set to independently participate in the load reduction bidding, a situation different from the reference appears.

The size of the DRC is the same as in reference, but it is divided into two. The market and participants' numerical data are applied in the same way as in Section 4.1, and the NE state is as follows in Table 6.

In the “2DRC” case, highlighted in Table 6, the same incentive (7.858) is given to the two DRC by the DRA, and

Table 6. Comparative results with the number of DRCs

Cases	*P*	*Q*	d_1	d_2	x_1	x_2	θ_1	θ_2	η
DRC+NRC	37.63	188.15	135.31	67.65	-	14.82	-	0.430	1.787
1 DRC	37.18	185.89	203.53	-	17.64	-	0.512	-	9.742
2 DRC	34.82	174.11	137.65	68.82	16.18	16.18	0.534	0.534	7.858
4 DRC	31.15	155.75	84 56	42 28	13.8 13.8	13.8 13.8	0.57 0.57	0.57 0.57	4.919

Table 7. Comparative results of monopoly and duopoly of DRA

Cases	*p*	*Q*	d_1	d_2	x_1	x_2	θ_1	θ_2	η_1	η_2
Monopoly A	37.18	185.9	203.53		17.64		0.512		9.742	
Monopoly B	34.823	174.11	137.65	68.82	16.18	16.18	0.534	0.534	7.858	-
Duopoly	35.25	176.3	137.3	68.64	15.56	14.10	0.508	0.471	5.791	1.942

also the bidding parameters of the two DRC have the same value (0.534). The reason of the same values is because the slope (β) and the maximum value (α) of y-intercept in the bidding function are the same in both DRC, even though the two DRC have different demand functions.

The first line (DRC+NRC) in Table 6 corresponds to the result in Section 4.1 where load D_1 does not participate in DR. It is natural that the case of “2DRC” results in more load reduction and lower market price than the case (DRC+NRC), since more customers participate in the DR.

One thing to note is the comparison of “1DRC” and “2DRC” with the same scale of load. The case of “1DRC” is the same as the reference in Section 3.1, where the entire load is participating in the bid of load reduction. In the case of “2DRC”, however, two DRC participate in the bidding independently for load reduction. Comparing the results, “2DRC” increases the load reduction and lowers the market price more than "1DRC".

The number of DRCs participating in the bidding was further subdivided into four, as represented in the case “4DRC”. The slope (r) of the demand function is 2.0, 3.0, 4.0, and 6.0, leaving the y-intercept (a) of the demand function unchanged. In the four DRCs, the same bidding parameter and reduction amount are calculated because the same reduction cost function is applied. The total reduction (55.3=4x13.83) is further increased and the price is further lowered. Therefore, it can be deduced that there is a phenomenon in which the reduction is increased and the price is lowered when the number of independent DRCs is increased while maintaining the total demand characteristics and maintaining the same DRA. This suggests that the price of DR has been lowered as competition of DRCs for bidding has intensified, and this has also affected the electricity market.

4.3 Competition between DRAs

From the viewpoint of DRA, the situation referenced in Section 3.1 can be regarded as a monopoly in which a single DRA manages all the customers. Also in Section 4.2, one DRA is responsible for the entire DR with two DRCs, which is also a monopoly. We analyze the situation when this monopoly breaks down and another DRA enters to regroup and competes with each other. The conventional concept of the monopoly and oligopoly makes the qualitative results easily predictable, but the analytical result is not so simple.

It is assumed that a new DRA has contracted the load D_1 in Section 4.2. Thus, two DRCs are contracted with two DRAs respectively. The demand functions are the same as in Section 4.2, and the bidding functions (α, β) and the reduction cost function (γ) are also applied as shown in Table 1. The results of NE state are as follows in Table 7.

The situation where the DRA is monopolistic is covered in Section 3.1 and Section 4.2. In Section 3.1, the entire load is involved in the reduction bidding as a single entity (Monopoly A). In Section 4.2, two DRCs participate independently in the bidding (Monopoly B). Duopoly in Table 7 show that two DRAs choose incentives of 5.79 and 1.94, respectively, and the two DRCs bid 0.508 and 0.471 resulting in load reduction of 15.56 and 14.10, respectively.

The price in Duopoly is lower than that in Monopoly A, but higher than in Monopoly 2. On the contrary, the amount of load reduction is in reverse. Therefore in terms of economic efficiency, the order is as follows: MA (Monopoly A) < D (Duopoly) < MB (Monopoly B). The conventional concept that monopoly is inferior to duopoly in economic efficiency is not consistent with this result about competition between DRAs. This paper tries a different approach to explain this phenomenon.

The reason why the D is superior to MA is analyzed because there are two DRCs that compete with each other intensively. The competition between DRCs has a greater impact on the market than competition between DRAs. It is explained by the reason that the DRC impacts directly on the electricity market by performing the bidding, while DRA affects the market indirectly and weakly by presenting incentives to DRC. So how can we explain the superiority of MB over D? This can be explained by analyzing the characteristics of incentives in the following.

4.4 DRA’s selection for incentive

The incentives of DRA to DRC have been explained to

Table 8. Comparative results with DRA coalition

Cases	p	q	d_1	d_2	x_1	x_2	θ_1	θ_2	η_1	η_2
w/o Coalition	35.25	176.3	137.3	68.64	15.56	14.10	0.508	0.471	5.791	1.942
Coalition A	33.34	166.7	138.9	69.44	14.86	***26.78***	0.538	***0.836***	5.872	-
Coalition B	31.40	157.0	140.5	70.25	***28.30***	25.46	***0.923***	0.852	-	-

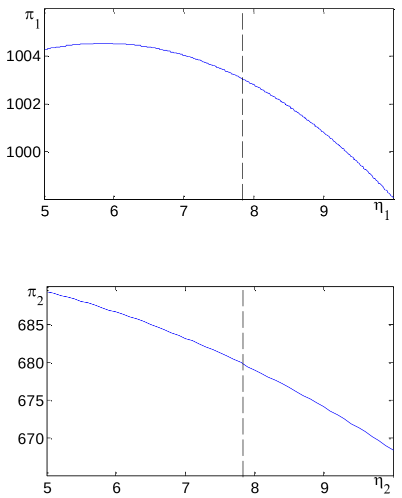

Fig. 4. Marginal profits of DRAs with uniform incentive

be effective in the integrated market in Section 3.3. If so, we compare the uniform incentive and multi-incentives that are presented by multiple DRAs independently. Which would be more economically efficient?

In this paper, the terminology of monopoly is used for DRA competition where a uniform incentive is presented in the market. Therefore, the point of superiority of MB over D in previous section is accepted as the uniform incentive is more desirable than two incentives presented by two DRAs. In the Duopoly situation in Table 7, the uniform incentive 7.86 gives better results to the market than two incentives, 5.79 and 1.94 from competition between DRAs. If the two DRAs use the uniform value, then the market-clearing results are as in the case of MB in Table 7 with better efficiency. Why do the DRAs not use the uniform incentive for better result? We look into the marginal profits of DRAs for the reason of not keeping the uniform incentive 7.86.

The graphs in Fig. 4 are made by changing the DRAs incentive with keeping the opponent's incentive fixed as 7.86. As shown in the figure, it can be seen that the profit is increased by lowering the incentive gradually from 7.86. Therefore, the incentive of 7.86 can be chosen by neither. If we keep the choice of 7.86 purposely, the sum of the profit is 1003 + 679 = 1682. However, when the incentives in NE of duopoly are selected, the total profit is only 1668 by summation of 978.4 and 689.7. This is similar to the prisoner's dilemma problem in game theory. That is, the two rational DRAs do not cooperate, even if their choice of uniform incentive will be better to them.

5. Coalition between DRA and DRC

5.1 NE of coalition

Since the DR system has a short history, experiences and researches for the DR system are insufficient. It is necessary to try various improvements on the DR market design and operation method. The coalition between DRAs and DRCs, as well as the competition, is worth analyzing.

DRA is usually separate from electricity consumers, but some consumers may participate in business of DRA directly. We examine how DRA and DRC affect the market when they are associated. If a DRA and a DRC are combined into a coalition, the purpose of the coalition is to maximize the benefits added up of each as defined in 2.2 and 2.3. Therefore, the benefit of the coalition is represented by the following (4).

$$max_{\theta_j}\left\{\pi_j^{AC} = p_0 d_{0j} - \epsilon \cdot p \cdot (d_j - x_j) + \epsilon \cdot p \cdot x_j - C_d(x_j)\right\} \quad (4)$$

Since the DRA and the DRC jointly perform the bidding of the load reduction, the incentive parameter used by the DRA to the DRC becomes unnecessary. The combined company will be able to receive the payment to the DRA from the market, as well as play the role of DRC to bid directly. Therefore, incentive is excluded from the strategic variables of the combined company, and only the bid parameter remains. In the definition in (4), there are four terms with no incentive parameters. The first and second terms correspond to payment savings of the DRC for the electricity use due to the DR. The third is the market value of the load reduction of DRC, and the last is the reduction cost.

5.2 Impact of coalition and competition

In the case of DRA Duopoly in Section 4.3, one of the two DRAs and one of the two DRCs are set to join the coalition. The NE state is calculated and compared with the result of DRA Duopoly as shown "w/o coalition" in Table 8.

In Table 8, "Coalition A" is an alliance of DRA_2 and DRC_2, and the incentive parameter (η_2) does not appear. The result of "Coalition A" shows that the alliance bids aggressively so that willingness (θ_2) rises to 0.836 from 0.471. As a result, the load reduction (x_2) is increased to 26.78 from 14.1. The profits of DRA_2 and DRC_2 in the coalition are 1245.8 and -3.73, respectively, and the sum of two profits is 1242.1. The excessive willingness of DRC_2 in bidding led to a significant increase in the cost of load reduction, resulting in a negative gain for DRC_2. Thus, the profit of the DRA_2 is greatly increased, so that the integrated profit is maximized.

If not federated, DRC_2 will not make this choice with a negative gain. As a result, the benefit of the alliance increases, the load reduction increases, and the market price decreases, so the coalition of DRA and DRC has a positive effect on the market. "Coalition B" in Table 8 is a case of two coalitions where DRA_1 and DRC_1 join additionally. The results show that the load reduction (x_1) is greatly increased due to the aggressive bidding (θ_1), and the market price is also lowered to 31.4.

Table 8 shows the coalition between DRA and DRC. However, coalition between DRA and DRA can be considered a different type of coalition. In the case of DRA duopoly where there are two DRAs and two DRCs, if the two DRAs join the coalition, then the setting of the participants is identical to the case of “monopoly B” having one DRA and two DRCs in Table 7 in 4.3. In the result of the coalition between DRA and DRA, the market price is 34.82, which is lower than that (p=35.25) in "No coalition" in Table 8, but higher than that (p=33.34) in the DRA-DRC coalition. It can be said that the coalition of DRA-DRA is better than no coalition, but less effective than the coalition of DRA-DRC.

Further steps in coalition are considered. From the case of “Coalition B” in Table 8, where there are two coalitions of DRA-DRC, we consider another coalition between the two alliances. This is a form in which the total load and a monopoly DRA seek common benefits. The market price of this big coalition is 33.54, which is higher than the price, p=31.4, in the latter coalition. So it is not always true that more coalitions lead to better results.

The former situation is complicated in that the problem of competition or coalition is mixed up with the problem of DRA or DRC. As a result of NE calculations for various situations, we can summarize the influential priorities of the four factors that affect the price of the electricity market. The larger the size of the load involved in the DR, the greater the number of independent DRC for bidding of load reduction, the greater the number of DRA-DRC coalitions, the fewer the number of DRAs independently presenting the incentive, the better the effect of DR to the market. However, these priorities are not absolute because the four elements function independently.

6. Conclusion

The market-clearing price of DR should be formed using economic principles for increasing the economic effect of DR in the electricity market. In order to do this, appropriate DR market design should be developed. In this study, DRA is introduced to induce load customers to join the DR market. The DRA strategically uses the incentives to DRC, and DRC participates in bidding by using strategic parameters in consideration of DR pricing, incentives, and costs of load reduction.

Because market participants choose strategy variables to maximize their own profits, we proposed formulations of their profits and appropriate calculation techniques to find the Nash Equilibrium in game theory. The effects and implications of the proposed parameters are explained by case studies. The effect of the price correction factor is analyzed by which the market operator affect DR price. The introduction of DRA incentive is verified to contribute to increase the DR effect.

The effect of DR is affected by the form and extent of competition and coalition between DRA and DRC in the market. In general, the greater the competition, the better the effect of DR, but sometimes the more cooperation between participants of a certain type, the better the effect. A number of case studies have been conducted to identify factors affecting the market impact of DR and to consider their impact priorities. These results are expected to help improve the design and operation of the DR market to increase the scale of DR and to evaluate the value efficiently.

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