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The incentive announcement effect of demand response on market power mitigation in the electricity market

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ABSTRACT

The incentive announcement effect of demand response (DR), which can mitigate exercising of market power, was assessed using a game theory method. To analyze player behaviors, the profit functions of generation companies, DR consumers, and normal consumers were formulated and their best response functions derived. Because the implementation method of a pre-announced DR incentive with game theory has not been studied before, a sequential game that can make a normal consumer a leader was considered. The leader's strategy, i.e., the incentive level, is determined by a neutral agent to prevent overuse of the demand resource. With this procedure, market equilibrium can be obtained by solving the Stackelberg game. An analytical solution for market equilibrium was derived for a simple case; simulations were used to confirm the maintenance of tendencies in a more complex case. As a result, the market clearing price was reduced and a fairer distribution of the surplus was achieved compared with the result of the oligopoly condition case. This indicates that the exercise of market power is affected by the incentive announcement procedure and market power can be mitigated.

1. Introduction

Before the implementation of electricity markets, the system operator (SO) considered demand to be fixed and scheduled operation plans based on generation resources. Because the balance of supply and demand has to be maintained simultaneously in an electricity system, there were inefficiencies in the use of generation resources. Furthermore, the peak load level can increase dramatically, and the load profile has diversified through improvements in technology. Given these complexities, additional peak generators were added for short-term usage.

Historically, SOs have attempted to find other methods to balance supply and demand; this has resulted in consideration of demand resources to curtail the load in balancing sequences [1–3]; thus, the reduction event is triggered by the SO and the reward for reduction is determined based on actual performance. This method, referred to as demand-side management (DSM), is considered to be merely an extra tool in the supply–demand balance, in which the consumers treat the electricity system in a passive way.

Over the last two decades, market mechanisms have been introduced into the electricity system, providing motivation for consumers to change their passive attitudes. However, the practical reaction of consumers in the electricity market has been weak due to the lack of infrastructure to send market signals to consumers. The profit from electricity market implementation was not gained totally on the demand side in the early days. The high penetration of advanced metering infrastructures (AMI), however, now enables consumers to participate in the electricity market to overcome this problem [4]. The appearance of price-responsive demand (PRD) has prompted the development of various tariffs that contain information on the wholesale market price. These novel tariffs, along with conventional DSM, are now referred to as “demand response” (DR). Thus, DR is now defined as a tariff or program established to motivate changes in electricity use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized [5,6].

Various studies have examined the effect of implementing DR programs into market mechanisms. In [7], modeling of the consumer considering self- and cross-elasticity was described and reflected in an operation planning method. The case study results showed a reduction in total generation cost and a market price reduction. Related research also sought to reflect consumer elasticity in conventional scheduling problems [8,9]. Other studies focused mainly on the effects of demand

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Nomenclature

$\pi_{i,o}$	Profit function of i in an oligopoly scenario
P_o	Market price in an oligopoly scenario
$q_{i,o}$	Generation quantity of i in an oligopoly scenario
$C_i(q_{i,o})$	Cost of i when quantity $q_{i,o}$ is generated in an oligopoly scenario
e	y-intercept of the inverse demand function
f	Gradient of the inverse demand function
Q_o	Total generation quantity in an oligopoly scenario
$\pi_{c,o}$	Profit function of consumers in an oligopoly scenario
$D(q)$	Inverse demand function
a_i	Coefficient of 2nd order term of cost function for i
b_i	Coefficient of 1st order term of cost function for i
c_i	Constant term of cost function for i
$q_{-i,o}$	Sum of generation quantity except i in an oligopoly scenario
$\pi_{DC,v}$	Profit function of a DR consumer in a voluntary DR scenario
k	Surplus ratio of a DR consumer
Q_v	Total generation quantity in a voluntary DR scenario
P_v	Market price in a voluntary DR scenario
q_v	Quantity of interruptible load program participating in a voluntary DR scenario
q_{dmax}	Maximum quantity of DR consumer's resources
$\pi_{DC,d}$	Profit function of a DR consumer in an incentive-announcement scenario
P_d	Market price in an incentive-announcement scenario
Q_d	Total generation quantity in an incentive-announcement scenario
q_d	Quantity of interruptible load program participating in an incentive-announcement scenario
I	Incentive level
$\pi_{NC,d}$	Profit function of a normal consumer in an incentive-announcement scenario
$q_{i,d}^*(I)$	Final generation quantity of i expressed by the incentive term in an incentive-announcement scenario
$q_d^*(I)$	Final demand reduction of a DR consumer expressed by the incentive term in an incentive-announcement scenario
$Q_d^*(I^*)$	Total generation quantity when the proper incentive level I^* is announced in an incentive-announcement scenario
$P_d^*(I^*)$	Market price when proper incentive level I^* is announced in an incentive-announcement scenario
S_g^{GE}	Supplier surplus when market power is exercised by capacity withholding
S_g^{GP}	Supplier surplus under conditions of perfect competition
S_d^{GE}	Consumer surplus when market power is exercised by capacity withholding
S_d^{GP}	Supplier surplus under conditions of perfect competition

reduction [10–12]. In [13], actual reduction results for Pennsylvania–New Jersey–Maryland (PJM), California ISO (CAISO), ISO New England (ISO-NE), and New York ISO (NYISO) were assessed and related efficiencies analyzed.

Despite the implementation of market mechanisms providing opportunities to improve efficiency on the demand side, a market power problem has arisen on the generation side with the potential to create inefficiencies in the electricity market [14]. Due to the characteristics of the power system, small variations in generation can cause massive changes in the energy balance and market price [15,16]. Some generation companies (GENCOs) exercise market power in various ways to maximize their profit; this can cause an unfair transition of surplus from consumers to GENCOs. Several studies have analyzed the market equilibrium when market power is exercised in the electricity market. The Cournot model, to explain withholding generation capacity; the Bertrand model, to explain strategic price bidding; and Supply Function Equilibria (SFE), to explain the generation cost function and demand uncertainty, have been suggested as analytical methods [14,17–20]. *Ex ante* and *ex post* methods have been studied to resolve the market power problem [14]. Above all, as the response capability of the demand resource has improved, the management of market power using demand resources has focused on the expectation of reducing market prices and dead-weight losses [21]. This is because the fundamental resolution of market power can be obtained by managing demand quantities in a market system. Related studies on mitigating market power using DR deal mainly with demand elasticity [22,23]. Studies have shown that PRD can control the rise in market prices.

However, there is a need to reflect the circumstance in which interruptible loads and PRD are both used, because most research to date has concentrated on DR programs and therefore merely considers mutual influences between DR programs [24–27]. Related advanced research that considers both programs has mostly analyzed the effect on retail markets, while the wholesale market price is regarded as fixed [28]. In [29], the effect of incentive level on a given GENCO's strategy was analyzed; however, the benefit of the first mover (the agent who determined the DR incentive) was not considered. Reference [30] introduces the determining method of proper interruptible load quantity to prevent capacity withholding by GENCOs in the market circumstance. However, the incentive determination method and sequential procedure between the interruptible load program day-ahead market are not considered. Reference [31] examined the SFE formulation method of the impact of interruptible load contract to the electricity market; the authors tried to contain the interruptible load to the SFE model in which several techniques were suggested. The reference mainly focused on the implementation scheme, but the incentive level determination method was not considered.

From advanced studies, the market procedure that reflects the incentive announcement period is merely studied. Although a number of researchers have attempted to guess the impact of sequence of DR program and market operation intuitively, there is a need to analyze the market equilibrium that contains strategic behaviors and market procedures that reflect the incentive announcement period.

In this study, the assessment of the market power mitigation effect by incentive-based DR was examined for the case in which there is PRD penetration into the market. Each player's profit maximization strategy was analyzed using game theory analysis. The Stackelberg model was used to find the market equilibrium when the incentive announcement effect was contained. In this paper, analytical formulations of a sequential game are described, and the related market equilibrium is shown for a simple case. For a more complex case, the tendencies confirmed in the simple case are checked numerically. Our paper can contribute to the effective operation of an energy market by reflecting the appropriate effect of DR. It is suggested that further studies on the game theory approach may provide opportunities to resolve future integrated resource planning and new market operations [32,33].

The remainder of this paper is organized as follows. Chapter 2 introduces the basic assumptions and limitations for a clear understanding of the study. Chapter 3 reviews market equilibrium under oligopoly conditions and describes voluntary DR in the wholesale market. Chapter 4 provides a comprehensive explanation of the incentive announcement effect and an analytical solution is derived for a simple case. In Chapter 5, a complicated case is studied with a simulation, tendencies are checked, and results are analyzed. In Chapter 6, conclusions and future work are described.