경쟁적 전력시장에서의 적정 직거래 계약가격 설정에 관한 연구

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Analysis of Mechanism Design for the Optimal Bilateral Contract in the Competitive Electricity Market

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Abstract - Although electricity market structures may be different from each country, they have a long-term forward market and a short-term spot market in general. Particularly, a bilateral contract transacted at a long-term forward market fixes the electricity price between a genco and a customer so that the customer can avoid risk due to price-spike in the spot market. The genco also can make an efficient risk-hedging strategy through the bilateral contract. In this paper, we propose a new mechanism for deriving the optimal bilateral contract price using game theory. This mechanism can make the customer reveal his true willingness to purchase so that an adequate bilateral contract price is derived.

Key Words : Competitive Electricity Market, Bilateral Contract, Mechanism Design, Game Theory.

1. Introduction

In many parts of the world, the electricity industry is undergoing unprecedented changes. The essence of these changes is to establish the deregulated and competitive electricity market. Electricity is therefore not supplied by traditional vertically-integrated utilities but transacted between gencos and customers with total or partial competition.

Although electricity market structures are different according to each country's condition, they generally have a long-term forward market and a short-term spot market. Spot prices are set by gencos' and/or customers' bids (practically retailers' bids) at the electricity pool market. Studies on these strategic behaviors in the spot market have been performed extensively [1]. If we have only a spot market, the efficient power system operation may be accomplished through spot prices which are sent to gencos and customers as price signals. In this situation, however, gencos and customers are exposed to risks caused by extremely volatile and unforecastable spot prices. The California electricity crisis is a proof that the electricity market depending on low spot prices without hedging is very risky [4].

Bilateral contracts which are bargained directly or transacted at a long-term forward market between gencos and customers can be one of solutions to arrange the problems related to these risks [5]. Since bilateral contracts fix electricity prices in advance, customers can avoid risks due to price-spikes in the spot market through these contracts. Experiences in England & Wales, Norway, Australia, and San Diego etc. show that most customers prefer electric charges fixed by bilateral contracts to linking with spot prices. As a result, electricity markets are likely to be advanced as follows: Most customers take electricity service at fixed rate from retailers and retailers enter into a variety of bilateral contracts as hedging arrangements to manage the risk of these fixed rate sales. Gencos hold a portfolio of bilateral contracts that provide a significant part of their income and new entries in generation compete with existing gencos for bilateral contracts. Therefore, the spot market provides appropriate price signals at the margin to unhedged generation and load for the supply-demand balancing.

In this environment, gencos can also device efficient risk-hedging strategies to minimize uncertainty at electricity sales and secure a major portion of revenues through the bilateral contracts. However, studies on the long-term forward market, particularly price-setting mechanism at bilateral contracts, have been merely elementary investigations on price estimation but there are not substantial researches from contracting parties stand.

In this paper, we provides a mechanism design to establish an adequate bilateral contract. This mechanism makes a customer reveal his true willingness to purchase electricity so that the optimal bilateral contract price can be derived.

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2. Information Problem of the Bilateral Contract

A customer may purchase a part of his demand through bilateral contracts [7]. At this time, contract amount may be varied according to his preference to risk of price-spike in the spot market. The customer can minimize risk of purchasing electricity through bilateral contracts and obtain opportunities to minimize his total purchasing cost through bids in the spot market. Therefore, the customer may resign his purchasing amount to achieve these two goals simultaneously.

A genco may also minimize risk of selling electricity and maximize its own profits simultaneously. For these goals, the genco should device the optimal electricity-sales portfolio by estimating the customers' expected bilateral contract amount exactly. If the genco sets the bilateral contract prices without regard for customers' willingness to purchase, customers will have an incentive to distort their willingness to purchase for the maximum benefits (i.e. the customer's surplus) and it will result in a loss of opportunity for the genco to increase its profits. For example, suppose that a genco sets a bilateral contract price too high. Then, a customer may purchase electricity less than his expected through this bilateral contract and the genco may be exposed to high risk due to a loss of opportunity for the stable electricity-sales in consequence. On the other hand, if a genco sets a bilateral contract price too low, then a customer may purchase electricity more than his expected. As a result, the genco may miss an opportunity to increase its profits due to decreasing sales amount to other customers and/or spot market.

However, the genco cannot exactly acquire any customer's willingness to purchase the bilateral contract amount, since it is each customer's private information. Therefore, the genco should design the mechanism to device the optimal electricity-sales portfolio without this customer's private information.

3. Mechanism Design

To solve this information problem, an economic technique, called as "mechanism design", has been developed. Thisis special form of incomplete information game. Mechanism means a set of game rules performed by an uninformed player, "principal" and an informed player, "agent" [13].

The mechanism should following features to satisfy the mechanism-designer's goals. First, to make a contract with the agent, the principal should offer him a contract that guarantees benefits more than his reservation utility. If the agent expects his benefits by this contract to be less than his reservation utility, the agent may reject the contract. This constraint is called as the individual rationality or participation constraint.

The mechanism should also satisfy the incentive compatibility constraint simultaneously. This means the constraint that makes the agent reveal true private information as his optimal strategy. In mechanism design, this state is called that "truth-telling" the agent's private information is the equilibrium strategy. However, the incentive compatibility constraint does not always guarantee that the agent does truth-telling. It solely means that the agent may obtain maximum benefits in case of doing truth-telling.

3.1 Customer's Benefit Function

In this paper, we design the mechanism as follows. First, a customer offers a genco his bilateral contract amount. At this time, the offered contract amount needs not be identical to his true willing purchase amount (i.e. degree of aversion to risk of price-spike in the spot market).When the customer has offered his purchase amount, the genco will set the contract price on this offer. Figure 1 shows the overall flow on this procedure.

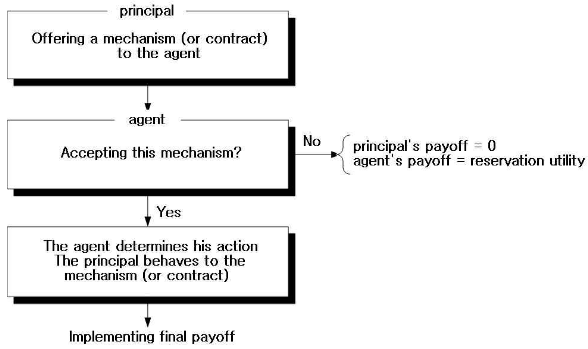

Fig. 1 Structure of mechanism design

According to the law of diminishing marginal utility in economics, the customer's marginal utility decreases in proportion to the electricity purchase amount. Assuming that the customer's marginal utility decreases linearly, the marginal utility function can be defined as follows:

$$u(q) = b_0 - kDq \qquad (1)$$

D is the customer's total demand and q is the degree of willingness to purchase through the bilateral contract (i.e. degree of aversion to risk of price-spike in the spot market) where $0 \le q \le 1$. Therefore, the customer's electricity purchasing amount from a genco through the bilateral contract is calculated as Dq. Since the value of q is the customer's private information, the genco cannot know this value. b_0 is the value of a unit electricity consumed first and k means the change rate of marginal utility for additionally consumed electricity. In this paper, we assume that the genco estimates exactly the customer's marginal utility function coefficients, b_0 and k.

The customer's total utility is the value of integral for this marginal utility function. Therefore, total utility for the marginal utility function defined at (1) is calculated as follows:

$$U(q) = \int_0^q u(q)\,dq = b_0 q - \frac{1}{2} k D q^2 \quad (2)$$

In this mechanism, the genco sets the bilateral contract price, λ on electricity purchase amount offered by the customer. If the customer purchases his offered amount at the price set by the genco, then he can pay $P(q) = \lambda D q$. Therefore, the customer's benefit obtained by this bilateral contract is calculated as follows:

$$B(q) = U(q) - P(q) = b_0 q - \frac{1}{2} k D q^2 - \lambda D q \quad (3)$$

If the customer does not agree on this bilateral contract, that is, $q=0$, then he will obtain the zero benefit through this contract. This zero benefit is defined as the customer's reservation utility.

3.2 Contract Design

The genco should set adequate bilateral contract price on the customer's offered purchase amount so that it device the optimal electricity-sales portfolio. At this time, the genco should satisfy following constraints.

■ *Individual rationality constraint*

When the customer agrees on the contract at the price set by the genco, the customer's benefit obtained this contract should be larger than this reservation utility. That is, the bilateral contract price should guarantee the customer a nonnegative benefit.

$$\begin{aligned} &B(q) \ge 0 \\ &b_0 q - \frac{1}{2} k D q^2 - \lambda D q \ge 0 \end{aligned} \quad (4)$$

■ *Incentive compatibility constraint*

The customer should not distort his willingness to purchase from the genco's setting price. That is, the bilateral contract price should guarantee that the customer can obtain a maximum benefit by offering his true willingness to purchase.

$$\begin{aligned} &B(q) \ge B(\tilde{q}) \\ &b_0 q - \frac{1}{2} k D q^2 - \lambda D q \ge b_0 \tilde{q} - \frac{1}{2} k D \tilde{q}^2 - \lambda D \tilde{q} \end{aligned} \quad (5)$$

where, $\tilde{q}$ is the degree of willingness to purchase through the bilateral contract offered by the customer to the genco.

■ *Feasibility constraint*

When the bilateral contract is concluded at the customer's offered purchase amount, the genco should obtain a profit through this contract. That is, the bilateral contract price should be larger than a unit of service cost on this contract.

$$\begin{aligned} &\pi(\tilde{q}) = \lambda D \tilde{q} \ge C(\tilde{q}) \\ &\lambda \ge \frac{C(\tilde{q})}{D\tilde{q}} \end{aligned} \quad (6)$$

where, $\pi(\tilde{q})$ is the genco's revenue obtained by selling the contract amount $D\tilde{q}$ at a price of λ and $C(\tilde{q})$ is the service cost function paid to supply the contract amount $D\tilde{q}$.

Therefore, this mechanism, as a function on the customer's offered degree of willingness to purchase, should set the bilateral contract price satisfying the above constraints simultaneously.

3.3 Derivation of the Optimal Contract Price

If the mechanism is incentive compatible, the customer will recognize that his optimal strategy is to reveal his true willingness to purchase. Therefore, the genco derives first the price function satisfying this incentive compatibility constraint. Then, the genco evaluates whether the price derived on the customer's offered willingness to purchase satisfies the customer's individual rationality constraint and guarantees the genco's profit. Based on this result, the genco can set the adequate bilateral contract price.

In this mechanism, the genco minimizes the customer's expected additional benefit obtained by distorting his willingness to purchase so that the customer reveals his true private information. From (5), this additional benefit is calculated as follows:

$$\begin{aligned} AB(q,\tilde{q}) &= B(q) - B(\tilde{q}) \\ &= b_0(q-\tilde{q}) - \frac{1}{2} k D (q^2 - \tilde{q}^2) - \lambda D (q - \tilde{q}) \\ &= (q-\tilde{q})\left[b_0 - \frac{1}{2} k D (q+\tilde{q}) - \lambda D\right] \end{aligned} \quad (7)$$

Differentiating (7) on $\tilde{q}$, the following equation can be derived:

$$\frac{\partial AB(q,\tilde{q})}{\partial \tilde{q}} = -b_0 + kD\tilde{q} + \lambda D \quad (8)$$

By the first order necessary condition for minimization, equation (8) should be zero. Therefore, the optimal bilateral contract price is calculated as follows:

$$\begin{aligned} &-b_0 + kD\tilde{q} + \lambda^* D = 0 \\ &\lambda^* = \frac{b_0 - kD\tilde{q}}{D} \end{aligned} \quad (9)$$

Substituting this optimal bilateral contract price, λ^* for (5), the incentive compatibility constraint can be derived as follows:

$$(q-\tilde{q})\left[-\frac{1}{2}(q-\tilde{q})\right] \geq 0 \tag{10}$$

From (10), if the customer purchases electricity less than his true willingness through this contract, that is, if $q > \tilde{q}$, then $(q-\tilde{q})$ will be positive and $-\frac{1}{2}(q-\tilde{q})$ will be negative. Consequently, his expected additional benefit is negative. On the other hand, if the customer purchases electricity more than his true willingness, that is, if $q < \tilde{q}$, then the customer's expected additional benefit is also negative due to the negative value of $(q-\tilde{q})$ and the positive value of $-\frac{1}{2}(q-\tilde{q})$. Therefore, when the customer offers true willingness to purchase, that is, when $q=\tilde{q}$, he can obtain zero as the maximum of additional benefit. This shows that the incentive compatibility constraint is satisfied.

This bilateral contract price derived from the incentive compatibility constraint also satisfies the individual rationality constraint. Substituting this bilateral contract price for (4), the following condition can be derived:

$$\lambda \leq \frac{b_0 - kD\tilde{q}}{D} \tag{11}$$

Consequently, since the optimal bilateral contract price satisfies the individual rationality and incentive compatibility constraint simultaneously, the customer will tell the genco a truth by revelation principle [14].

Finally, if the above bilateral contract price also satisfies the feasibility constraint, (6), the genco can device the optimal electricity-sales portfolio by concluding the contract at this price.

3.4 Analysis on the Optimal Bilateral Contract Price

From (9), it shows that the optimal bilateral contract price has the following features:

- The optimal bilateral contract price function has a form decreasing in proportion to the customer's purchase amount. Therefore, the genco can induce the customer to increase his purchase amount using the price discrimination which has a discount form to reduce the price according to the customer's purchase amount. Consequently, this price discrimination provides an incentive to reveal the customer's true willingness to purchase for his benefit maximization.

- The bilateral contract price is calculated as the value of marginal utility on the customer's purchase amount divided by his total demand. If the genco exactly knows the customer's willingness to purchase, it can have the customer's whole benefit from this bilateral contract by setting the price as his possible maximum payment. That is, the genco can set the bilateral contract price for the value of the customer's benefit function to become zero, $\lambda' = (b_0 - \frac{1}{2}kDq)/D$ from (3) so that the customer's benefit comes into its profit. However, if the genco does not know the customer's q exactly, then the bilateral contract price will be set as $\lambda^* = (b_0 - \frac{1}{2}kD\tilde{q})/D$ by (9). Consequently, this result causes the genco to miss the chance of profit increase as $\lambda' - \lambda^* = \frac{1}{2}kq$ per a unit of selling amount. This is "the information payment"that the genco pays the customer to reveal his true willingness to purchase. Therefore, in this case, the customer can obtain the maximum benefit as $(\lambda' - \lambda^*)Dq = \frac{1}{2}kDq^2$ by revealing his true q.

4. Conclusion

In this paper, we design a new mechanism for deriving the optimal bilateral contract price using game theory. Since the customer's willingness to purchase through the bilateral contract is his private information, a genco cannot know this value. This mechanism can make the customer reveal his true willingness to purchase so that an adequate bilateral contract price is derived for the genco to device the optimal electricity-sales portfolio.

Although results in this paper are a little analytic, we expect that these results provide basic information for the bilateral contract design in future wholesale competitive electricity market. Moreover, for the complete bilateral contract design, we expect to perform additional studies on considering multiple customers and estimating the customer's benefit function.

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