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Exploring the strategy of direct power purchase transactions in the power market based on game theory

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Abstract: In the mode of direct power purchase transactions for large customers, improving the efficiency of transactions is a prominent issue. The transaction volume and unit price in the electricity market belong to public information, which is the basis for negotiating the price between large users and power generators, and the final transaction price is lower than the market transaction price, which becomes the motivation for large users to choose to continue the transaction. In the game on the transaction volume and transaction price, the expectations of both parties on the transaction price and the type of both parties belong to private information. In this paper, based on the knowledge of the static game with incomplete information, the conditions for transaction realization are constrained, the payment matrix is expressed based on the consideration factors, the Bayesian Nash equilibrium model is established to design the offer strategy, and the expression of the optimal response strategy is finally given.

1. Introduction

Among many types of users in China, large industrial users, who concentrate 70% of electricity consumption, need to participate in demand response more urgently to improve the efficiency of electricity resource allocation because of their large individual electricity consumption, faster load adjustment and all-weather electricity consumption [1]. The electricity market can be divided into medium and long-term trading market, futures and options trading market, day-ahead trading market, auxiliary services trading market and real-time trading. Among them, the day-ahead trading market is for implementing medium- and long-term contract power and discovering day-ahead market prices so as to develop unit start-up and shutdown plans that meet grid safety and economy. The power generation companies bidding in the spot market declare the electricity energy offer curve for the operating day in the day-ahead market, including information such as the 96-point power-price for the operating day.

With the development of China's electricity trading market, demand-side management, which aims to achieve structural allocation efficiency, has been widely used. Direct purchase of electricity by large consumers means that consumers who consume more than a certain amount of electricity can sign bilateral trading contracts directly with independent power producers [2]. Currently, there are three types of direct power purchase transactions: bilateral transactions, power pools and consortia with bilateral contracts. Bilateral transactions are a more flexible way of trading, provided that all bilateral transactions are reported to the system operator in advance and that practical contracts are in place to ensure that grid security con- straints are met. [3] In markets that allow bilateral transactions, generating companies can ne- gotiate individually with customers. The implementation of direct power purchase transactions for large consumers marks the beginning of a shift in the domestic electricity market from a single generation-side market to a bilateral market with load-side access. [4]

With the development of game theory research, there are more and more studies on the supply and demand equilibrium model of electricity market from the perspective of game the- ory, and the applications are very extensive. Electricity is a kind of non-storable commodity, because of the uncertainty of real-time changes in electric energy trading, which makes the two sides of the trading market of electric power subject to constraints from the third-party ex- change-trading needs to ensure the reliability and stability of system power supply, which puts forward requirements for the technical level of power suppliers, and the power suppliers who meet the requirements have relatively more say in the price, therefore, the electric power There- fore, the electricity trading market is not a perfectly competitive market, and the price sensitiv- ity of buyers and sellers is higher than that of general commodities, and there is more room for negotiation and bargaining flexibility.

1.1. Problem Background

The objective of power generation enterprises is to maximize profits while ensuring that they can recover generation costs, and the objective of large users is to minimize the cost of electricity purchase. Under the condition that the generation, transmission and distribution mar- kets are fully opened, the objective function of the electric energy trading market is to maxim- ize social benefits, and this paper discusses the situation that only the generation market is opened, and the expectation of large users is to minimize the cost of electricity purchase. In this paper, we discuss the generation enterprises and large consumers, and the optimization plan of unit start/stop or combination belongs to the internal affairs of generation enterprises, and the quotation of power plant includes the cost of unit start/stop and other factors.

This is because if the transaction price exceeds the previous market price, the parties will not negotiate but will submit the price information to a third party, i.e., they will adopt the traditional method of selling and purchasing electricity. In addition, it is assumed that the val- uation of both parties and the type of large customers are private information, and factors such as demand preferences and personality traits of large customers are personalized information that cannot be collected in full. This paper is based on the premise assumption that the buyer and seller do not know each other's origins in the first negotiation, and does not consider the possibility of evaluating each other's strengths before the negotiation and thus adopting a price- setting strategy. To simplify the problem, the first simultaneous bids from buyers and sellers are set to avoid the first-mover advantage.

In the one-to-one two-way auction model, let the valuation of electricity *q by large users* be V_b, and the valuation of electricity generators be V_s, and the valuation of both parties for the known traded electricity q is private information. The buyer and seller hold the maximum price limit and the minimum transaction price for the electricity q transaction price respectively, i.e., for large users, the maximum transaction price cannot exceed $V_b\,(1+\delta)$; for generators, the minimum transaction price cannot be lower than $V_s\,(1-\theta)$, where δ and θ are tolerance levels, the size of which depends on the scale strength of the respective enterprises, and the size of the transaction price limit range is an important reference to reflect the bargaining power of both parties.

1.2. Types of game participants

In the context of power trading, the outcome of one-to-one bargaining negotiations de- pends not only on the bargaining power of the two parties and the day-ahead clearance price, but also on factors such as the type of parties involved in the game.

In the context of this paper, two types of large users are set to exist: innovative low-energy-consuming large users (*A*) and traditional high-energy-consuming large users (*B*); there is only one type of generators, all of which are denoted by letters below.

Analyzing from the game theory perspective, let the large user be the insider 1 and the power producer be the insider 2, and their type set is.

$$T_1 = \{t_{11} = A, t_{12} = B\},\ T_2 = \{t_2\}$$

The action sets for large users and generators are

$$A_1 = \{a_1 = \text{buy},\ \ a_2 = \text{not buy}\}\ A_2 = \{b_1 = \text{sell},\ \ b_2 = \text{not sell}\}$$

For Participant *A*, mastering the new technology can reduce processing costs, expand mar- ket share, and form economies of scale. Advanced technology is its natural competitive ad- vantage, and thus its bargaining power is higher than that of traditional-type large user *B*. The range of acceptance of the highest price, i.e., is greater. δ

2. Model Building

2.1. Transaction realization conditions

During the bargaining process, the parties move up or down based on their respective valuations, and successful negotiations are marked by.

$$P_b(V_b) \geq P_s(V_s)$$

Where $P_b(V_b)$ is the bid of the large customer and $P_s(V_s)$ is the bid of the generator.

The game can continue for several rounds, and if the above conditions for a successful transaction are not met, the next round of negotiations can be conducted, and if the conditions are not met until one party exceeds the price range, the negotiations are declared broken, oth- erwise, the negotiations continue until the conditions are met.

2.2. Payment calculation

For generators, payments are calculated as.

Payment = (transaction price - generation unit cost) electricity

The transaction price is p, let the unit cost of generation be c, and the payment for the electricity generated by the generator trading at q is

$$(p - c) \times q$$

For large customers, payment is calculated by reference to the previous day's market elec- tricity clearing price, i.e.

Payment = (day-ahead clearance price - transaction price) electricity

The price of p_Q was cleared before the day, and the payment for the electricity traded by large customers at q was

$$(p_Q - p) \times q \text{ (where } p_Q \geq p)$$

In each round of negotiation, both parties need to pay a reciprocal time cost, let the time cost of each round be γ, if the parties the n round reach a deal, the total time cost is $n\gamma$.

2.3. *Bayes-Nash* equilibrium model

It is common knowledge that both parties have private information about the valuation of the traded product and the type of large customer. In the bargaining process, there is an incom-plete information static game, in which generators choose to act based on their own generation costs and bargaining power (choose to continue to lower the price or abandon the bargaining), and large users choose to act based on their own type and the day-ahead clearing price (choose to continue to raise the price or abandon the transaction). The payment function for large users is stochastic, so the expected payment is used as the basis for decision making.

Although generators cannot accurately determine each other's types, they know each oth-er's decision space and the probability distribution of large user type vectors is common knowledge.

2.4. Quotation Strategy

Myerson and *Satterthwaite* have shown that for a hypothetical equilibrium distribution of valuations, the expected payoff of the insider in a linear equilibrium is higher than any other *Bayes-Nash* equilibrium of the game, so this paper adopts a linear offer strategy with specific variation factors for large users and generators, denoted as Δb and ΔS, respectively.

When the offer reaches the n round, the generator's offer strategy is

$$P_s(V_s) = V_s - n \times \Delta S \times V_s$$

The large user offer strategy is. $P_b(V_b) = V_b + n \times \Delta b \times V_b$

Where ΔS and Δb are constants between [0,1].

When $P_b(V_b) \geq P_s(V_s)$ is used, it is completed with. $p = \frac{P_b(V_b) + P_s(V_s)}{2}$

When the price quoted by both parties exceeds $V_b(1+\delta)$ or falls below $V_s(1-\theta)$ and the condition $P_b(V_b) \geq P_s(V_s)$ is not met, then the bargaining is terminated and the negotiation breaks down and both parties bear the cost of the time spent on the negotiation.

2.5. Payment matrix representation

The insider 1 (large user) has the choice to buy or not to buy when the type is *A*, as de-scribed above, and the strategies are noted as $\{a_1, a_2\}$, respectively, and has the same choice space when the type is *B*. Thus the set of strategies for insider 1 is

$$S_1 = \{(a_1, a_1), (a_1, a_2), (a_2, a_1), (a_2, a_2)\}$$

The insider 2 (generator) can choose to sell or not to sell, and the strategy is noted as $\{b_1, b_2\}$, so the set of strategies for insider 2 is

$$S_2 = \{b_1, b_2\}$$

When the insider 1 is type *A*, when the bargaining proceeds to the n round, the following situation is analyzed.

If bidders 1 and 2 decide to trade, bidders 1 earn the difference between the day-ahead liquidation price and the transaction price, and bidders 2 earn the difference between the trans- action price and the cost.

If bureau 1 decides to buy, but bureau 2 decides to terminate the negotiations and reject the deal, indicating that the bargain is lower than bureau 2's price expectation, i.e., $p \le V_s\ (1-\theta)$, for bureau 2, the loss is only the cost of time spent on n rounds of bargaining, for bureau 1, there is not only a loss of time cost, but also a loss of the deal that could have been reached but was missed. The loss of a deal that could have been achieved if the deal price was exactly the minimum expected by insider 2 is the difference between the day-ahead liqui- dation price and the deal price.

If bureau 2 decides to sell, but bureau 1 refuses to trade, it means that the bargain is beyond what bureau 1 can pay, i.e. $p \ge V_b\ (1+\delta_A)$, for bureau 1, the loss is only the cost of time spent on the n round of bargaining, for bureau 2, there is not only a loss of time cost, but also a loss of the deal that could have been reached but was missed. If the deal price is exactly the highest paid by insider 1, assuming $p_Q\ \ge V_b\ (1+\delta_A)$, the loss of the deal that could have been achieved is the difference between the day-ahead liquidation price and the deal price.

If both parties decline the transaction, each bears the cost of time.

When the inning 1 is type A, the payment matrix is represented as follows.

$$\begin{array}{ccc} & b_1 & b_2 \\ t_{11}\ \begin{matrix} a_1 \\ a_2 \end{matrix} & \left[\begin{matrix} ((p_Q-p)q,(p-c)q) \\ (-n\gamma,[c-V_b(1+\delta_A)]q-n\gamma) \end{matrix}\right. & \left.\begin{matrix} ((V_s(1-\theta)-p_Q)q-n\gamma,-n\gamma) \\ (-n\gamma,-n\gamma) \end{matrix}\right] \end{array}$$

When the inning 1 is type B, the payment matrix is expressed as

$$\begin{array}{ccc} & b_1 & b_2 \\ t_{12}\ \begin{matrix} a_1 \\ a_2 \end{matrix} & \left[\begin{matrix} ((p_Q-p-\eta)q,(p-c)q) \\ (-n\gamma,[c-V_b(1+\delta_B)]q-n\gamma) \end{matrix}\right. & \left.\begin{matrix} ((V_s(1-\theta)-p_Q-\eta)q-n\gamma,-n\gamma) \\ (-n\gamma,-n\gamma) \end{matrix}\right] \end{array}$$

2.6. Optimal response strategy and Bayes-Nash equilibrium solving

Easy to know $P(t_2\mid t_{11})=P(t_2\mid t_{12})=1\ P(t_{11}\mid t_2)=P, P(t_{12}\mid t_2)=1-P$

Given the strategy of insider 2 b_1, find the payout maximum of the response of insider 1, i.e., find the maximum of the first component of the first column of the two payout matrices, and find the optimal response strategy of insider 1 as (a_1,a_1); and

Given the strategy of insider 2 at b_2, the optimal response strategy of insider 1 can be found at (a_2,a_2).

For Bureau 1's strategy (a_1,a_1),

$$\begin{aligned} &\max_{b}\{Pu_2(a_1,b;t_{11},t_2)+(1-P)u_2(a_1,b;t_{12},t_2)\} \\ &=\max\{Pu_2(a_1,b_1;t_{11},t_2)+(1-P)u_2(a_2,b_1;t_{12},t_2),Pu_2(a_1,b_2;t_{11},t_2)+(1-P)u_2(a_2,b_2;t_{12},t_2)\} \\ &=\max\{Pq(p-2c+V_b(1+\delta_B))+cq-V_b(1+\delta_B)q-n\gamma,-n\gamma\} \end{aligned}$$

Similarly, for the strategy of inning 1 (a_2,a_2)

$$\begin{aligned} &\max_{b}\{Pu_2(a_2,b;t_{11},t_2)+(1-P)u_2(a_2,b;t_{12},t_2)\} \\ &=\max\{Pu_2(a_2,b_1;t_{11},t_2)+(1-P)u_2(a_2,b_1;t_{12},t_2),Pu_2(a_2,b_2;t_{11},t_2)+(1-P)u_2(a_2,b_2;t_{12},t_2)\} \\ &=\max\{-n\gamma,-n\gamma\} \end{aligned}$$

The strategy choice of bureau 2 brings the same payout, and according to the decision of bureau 1, bureau 2 tends to choose b_2.

In the actual trading game, the parties maximize their individual returns while minimizing risk, based on their respective costs, transaction prices, and the minimum/high price expecta- tions of the insiders, as well as the probabilities of the types derived from historical data.

3. Shortcomings and Improvements

The prerequisites for the bargaining model established in this paper are: the power trans- actions reached meet the grid constraints and pass the system operator's audit criteria; both parties to the game are perfectly rational economic agents. This paper argues that both sides of the game have sufficient historical transaction data to deduce the objective laws of various states and the significance of different states for their own payment.

However, in most cases, the participating parties do not respond quickly and optimally to complex changes in the environment; in fact, the parties belong to finite rational persons whose decisions are based on some kind of routines rather than rational calculations, and such routines are generally derived from the game history, which contains relevant information about how the opponents act. The next work will focus on building the optimal strategy model from the perspective of evolutionary games.

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