Research on Stackelberg Model of Power Market Considering Interruptible Load Contract

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ABSTRACT

This paper presents the interruptible electricity market Stackelberg game model of load under the contract in consideration, and the use of Monte Carlo solves the uncertainty of electric power demand simulation technology, the simulation proved that the interruptible load contract, and the interruption threshold reasonably can reduce the equilibrium price and volatility effect.

INTRODUCTION

Under the background of rapid development of new energy and smart grid in the world today, the demand response of electric power is paid more and more attention and application [1-4]. Interruptible load management is one of the important measures of demand response [5-8]. When the wholesale price of the market is too high or the energy resources are in short supply, the user can break or reduce the load according to the terms of the contract to ease the tension [9-11]. As the leader of the electricity market, generation companies have the ability to dominate the market [12-14]. Therefore, it is important to study the behavior of generators and predict the equilibrium of electricity market [15-16]. This paper established a Stackelberg game model in the wholesale market, which is based on market demand

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for the original model considering the interruptible load contract, and the market
demand model based on the wholesale market building Stackelberg model. The
original market model is no longer smooth, so a new method for solving the
equilibrium solution is needed. This paper determined by Monte Carlo simulation
technique to deal with the power demand, finally the simulation results validate the

**DEMAND FUNCTION OF GENERATORS CONSIDERING INTERRUPTIBLE LOAD**

In the future T (1 hour), in the power market of generation company and users
signed a contract of interruptible load, which indicate the interruptible load is $Q_k$, and the provisions of outage threshold price for $k_0$. $V$ is a part of the $Q$ interrupt
load. The power demand curve is shown in formula (1).

$$ D(p) = \begin{cases} A - bp & p < k_0 \\ (A - V) - bp & p = k_0 \\ (A - Q) - bp & p > k_0 \end{cases} $$

(1)

**STACKELBERG DYNAMIC GAME MODEL OF POWER MARKET CONSIDERING INTERRUPTIBLE LOAD CONTRACT**

Suppose there is a T (1 hour) in the future, there are interruptible load contracts
in the electricity market, and there are n generators, and the load demand $D$ is
expressed as formula (1). The cost of the generator $i$ is shown in the following
formula (2).

$$ C_i(q_i) = 0.5c_i q_i^2 + a_i q_i $$

(2)

In formula (2): $q_i$ is the power generation amount of i generator in T time; $C_i$
and $q_i$ are constants greater than zero and cost factor. The generation companies in
the electricity market are divided into two categories: one is the leading electricity
supplier, the number of which is $N_1$, and the electricity price is $P_1$. The other is the
follow-up producer, whose number is $N_2$, the electricity price is set to $P_2$. Ignoring
the constraints of the transmission network, the profit function of each generator $i$ is
same, such as the formula (3).

$$ \pi_i = pq_i - C_i(q_i) $$

(3)
The decision problem in the wholesale market can be described as the maximization of the run problem.

\[
\text{Max}_{q_i} \quad R_i = pq_i - C_i(q_i) \quad \text{s.t.} \quad q_i = D(p) - \sum_{j\neq i} q_j
\]

(4)

SOLVING METHOD

The First Kind of Situation

If the price is less than \(k_0\), which satisfy the assumptions of \(p < k_0\), \(p\) is the first category of the equilibrium solution, there is no implementation of interruptible load contract, so the interruptible load will not affect the result of market equilibrium.

\[
AN_2 - q_1 N_1 N_2 - 2N_2^2 q_2 - bc_2 N_2^2 q_2 - a_2 b N_2 = 0
\]

(6)

\[
q_2 = \frac{AN_2 - a_2 b N_2 - q_1 N_1 N_2}{2N_2^2 + bc_2 N_2^2}
\]

(7)

\[
F = \frac{AN_2 - a_2 b N_2}{2N_2^2 + nc_2 N_2^2} \quad G = -\frac{-N_1 N_2}{2N_2^2 + bc_2 N_2^2}
\]

(8)

\[
q_i^* = \frac{AN_i - N_i N_2 F - a_i b N_i}{2N_i N_2 G + bc_i N_i^2 + 2N_i^2}
\]

(9)

Returning \(q_1\) to \(s2(q2)\) can get \(q_2^* = F + Gq_1^*\). Therefore, the equilibrium result is \((q_1^*, q_2^*)\), while the zero hair electricity supplier chooses \(q_1^*\) in the first stage, and the trailing power supplier selects \(q_2^*\) in the second stage, which is the only sub refining Nash equilibrium of the dynamic game. The balance between supply and demand can be seen in formula (10).

\[
p = \frac{A - (N_1 q_1^* + N_2 q_2^*)}{b}
\]

(10)

Second Types of Situations

Suppose the wholesale price of electricity market is \(p > k_0\), then the demand curve is \(D(p) = (A - Q) - bp\). The method of equilibrium solution is similar to the situation one, so the equilibrium power generation and the equilibrium price of power market are the lower ones.
\[ p = \frac{A - Q - (N_1q_1^* + N_2q_2^*)}{b} \]  \hspace{1cm} (11)

**Third Types of Situations**

Assuming that the wholesale price of electricity market is \( p = k_0 \), the partial interruptible load \( V \) is interrupted, and \( 0 < V < Q \), the demand curve is expressed as \( D = (A-V) - bp \), and \( p = k_0 \) is substituted into formula (8), then the equilibrium solution of power market can be obtained.

\[ p = \frac{A - V - (N_1q_1^* + N_2q_2^*)}{b} \]  \hspace{1cm} (12)

**EXAMPLE SIMULATION**

Now suppose there are only 2 generators in a region, generator 1: \( a_1 = 10(/\text{$/MWh$}) \), \( c_1 = 1(/\text{$/MW2h$}) \), generator 2: \( a_2 = 10(/\text{$/MWh$}) \), \( c_2 = 1(/\text{$/MW2h$}) \). And in the future T (1 hour) market, the interruptible load is \( Q \), and the interruption threshold price is \( k_0 \). A obeys the normal distribution whose mean value is 190MW and the variance is \( \delta \), and the sample number is set to 10000.

**The Influence of Interruptible Load on Market Equilibrium**

Suppose the interrupt threshold price is \( k_0 = 105.0/$/\text{MWh}$ \), the effects of interruptible load on the mean and standard deviation of the market are shown in figure 2 and figure 3. The test results show that the implementation of interruptible load contract, The test results show that the price fluctuation decreases and the smaller the demand elasticity is, the more obvious the effect is when the interruptible load contract is executed.

![Figure 2. Equilibrium price p change trend chart affected by Q.](image1)

![Figure 3. The standard deviation of market price change trend chart affected by Q.](image2)
The Impact of Disruption Threshold Price on Market Equilibrium

Now suppose $Q = 20MW$, elastic parameter $b = 0.925(MW)^2 h/$, $\delta = 10$. Figure 4 is the curve of the output and profit of the generator 1 with the change of $k$. From the results, it can be concluded that the increase of the interruption threshold price will reduce the probability of the execution contract, but when the threshold value of the interruption is too large, the contract will not be executed, so the $k$ value will not affect the power generation and profit of the generator. So it is very important to set reasonable interrupt threshold. Figure 5 and Figure 6 shows that with the decrease in the market price interruptible threshold price, mean and standard deviation will be decreased.

CONCLUSIONS

When the electricity market, interruptible load contract can significantly reduce the market price and the price fluctuation inhibition, especially when the market uncertainty increase or reduce power the market price elasticity coefficient, the effect is more significant. The future of new energy generation will be more and more wide open; these power plants will lead to the market demand uncertainty, so
this research has practical significance. The appropriate choice of the threshold price can reduce the wholesale market price more effectively and restrain the price volatility effectively.

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