Analysis of Wind Power Enterprise Behavior in Electricity Market

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Abstract. With the advent of renewable energy, the electricity market needs to be reassessed and adjusted to maintain market fairness and stability. The starkelberg game model is established in which wind power enterprises act as leaders, their output is the profit-maximizing yield which constrained by the response function of the manufacturer (market operator). Taking other constraints into consideration, a multi-objective optimization model is established to find the starkelberg equilibrium strategy. Keep the system in equilibrium, in order to make better use of renewable energy, market operators change rules and state: increase the elasticity of demand, expanding market capacity, giving new energy subsidies. And wind power delivery deviations are punished by floating fine, companies take measure in advance in response to punish. The results show that under the condition of market equilibrium wind power enterprises can gain more profits than traditional model.

Introduction

The continuous warming of the climate is undoubtedly one of the most pressing problems facing mankind today. The biggest reason is carbon emissions, and fossil fuel power generation contributes one third to carbon emissions [1]. High fossil fuel prices and the desire to achieve energy independence have led to a transition from a fuel-led power system to one dominated by renewable energy. With the advent of renewable energy, the power regulatory authorities need to conduct reasonable analysis and correct assessment of the power market with more scientific means to reduce the risk of power market participants and stimulate the vitality of electrical enterprises. As the most mature renewable energy, wind energy has been widely used in power generation worldwide, and its market share is increasing year by year with a high growth rate [2]. However, wind energy is different from other distributed renewable energy. Large-scale wind power can be integrated into the power grid more centrally. Policy makers can no longer ignore the impact of wind power enterprises' behaviors on the power market. They need to make policies to balance wind power and conventional energy to achieve coordinated and reasonable operation of the power market.

Compared with other renewable energy sources, wind power is characterized by intermittency and randomness. Therefore, most of the current research focuses on reducing the uncertainty of wind power, so as to improve the profits of wind power enterprises and reduce costs. Literature [3] proposed a wind power consumption evaluation method based on day-ahead wind power prediction to realize scientific scheduling. Literature [4] proposes the option contract purchase method and proves that it can be used as a competitive method to reduce the uncertainty of wind power generation. Literature [5] proposed a two-tier optimization method to design effective incentive policies to promote the development of renewable energy. However, there is little literature on how policies affect the fairness and competitiveness of the electricity market. In this paper, wind power enterprises are placed in the environment of the electricity market, and the optimal method for wind power enterprises to adjust accordingly to adapt to changes and maximize their profits is analyzed under different rules formulated by the operators of the electricity market to maintain the fairness of the market.
Conduct Modeling of Wind Power Enterprises under Different Rules in the Power Market

Electricity Market Background

According to the time scale, the power market can be divided into forward market, short-term market, day-ahead market and real-time equilibrium market. Among them, the day-ahead market is the most important [6]. It determines the next-day clearing price and the bidding quantity of each power generation manufacturer according to the unit quotation and load forecast [7, 8]. Wind power enterprises play the role of price maker in the market and price deviator in the real-time equilibrium market. For different rules and states of the electricity market, such as bidding rules, deviation settlement, elastic demand, expansion of market capacity, new energy subsidies, fossil fuel energy tax, etc., wind power enterprises will make corresponding actions. The following will explore how the market rules corresponding to wind power business behavior can bring the most fair market competition environment and large profits of wind power enterprises.

Symbolic Rules

\( \pi_t \): Earnings of wind power manufacturers in time t (euro); \( \pi_{DA,t}, \pi_{RT,t} \): Day-ahead and real-time equilibrium market prices (euro); \( a_i, b_i \): Supply curve parameters of unit I (euro /MWh), (euro); \( \pi_{+t}, \pi_{-t} \): Wind power companies deliver more or less biased benefits in the real-time market than in the prior market (euro); \( p_{DA,t}, p_{RT,t} \): Price of the day-ahead market or real-time market within time t (euro /MWh); \( q_{DA,t}, q_{RT,t} \): Number of wind power manufacturers in the day-ahead market or real-time market within time t (MW); \( L_t \): Time t load (MW); \( q_{in,t} \): Number of unit I in time t (MW); \( q_{ex} \): The absolute deviation of \( q_{in,t} \) and \( q_{ex} \); \( q_{wd,t}, q_{wp,t} \): Number of wind power suppliers in time t (MW); \( P_{wBid,t} \): Tenders of wind power manufacturers within time t (euro /MWh).

Modeling

Find the Optimal Strategy to Achieve Equilibrium. Starkelberg’s game model is also called the dominant enterprise model, and the output determined by the leading manufacturer will be a profit maximization output constrained by the response function of the following manufacturer.

Enterprise 1 first chooses its own strategy -- output \( q_1 \), so enterprise 1 becomes a leader and is a wind power enterprise in this model. Enterprise 2 observes the output \( q_1 \) of enterprise 1, and then chooses its own strategy \( q_2 \). Therefore, enterprise 2 is a follower and the market operator in this model, whose function is to guarantee the equilibrium price of commodities and make the market clear. The output of enterprise 1 can be observed when enterprise 2 takes action, and the amount of enterprise 2 can be predicted when enterprise 1 decides the output. Therefore, the output of enterprise 1 determines the optimum of function \( \pi(q_1, q_2) \). The strategy \( (q_1, q_2) \) is stackerberg equilibrium [9].

Then the objective function of the leader is:

\[
\max \pi_t = \pi_{DA,t} + \pi_{RT,t} + \pi_{+t} + \pi_{-t}
\]

In which the:

\[
\pi_{DA,t} = q_{wDA,t} \cdot p_{DA,t}
\]

\[
\pi_{RT,t} = (q_{wRT,t} - q_{wDA,t}) \cdot p_{RT,t}
\]

\[
\pi_+ = -\mu_i \cdot \max(q_{wRT,t} - q_{wDA,t}, 0)
\]

\[
\pi_- = -\mu_i \cdot \max(q_{wDA,t} - q_{wRT,t}, 0)
\]

Market price is a function of output:
\[ p_{DA,t} = a \cdot \sum_i q_{i,t} = a(L_i - q_{wDA,i}) + b \]  

(6)

The following party is the market clearing model:

\[ \min q_{wDA,t} = \min \sum_i q_i \cdot q_{i,t} + b_i \]  

(7)

Other limitations in the model:

\[ q_{wDA,t} = q_{wBid,t} \]  

(8)

\[ q_{wPd,t} + q_{we,t} = q_{wRT,t} \]  

(9)

This model is nass equilibrium:

\[ \frac{\partial \pi}{\partial q_{wBid,t}} = 0 \]  

(10)

We can know that:

\[ q_{wBid,t} = \frac{-(\mu_i + \mu_\tau) \cdot F(q_{wBid,t} - q_{wPd,t}) + (a \cdot L_i + b + \mu_\tau - p_{PT,t})}{2a} \]  

(11)

Keep revision of projections + and schedule - to minimize the deviation between actual output and predicted value of wind power manufacturers within time t:

\[ \min q_{dev} = \sum_i |q_{wBid,t} - q_{wPd,t}| \]  

(12)

Here comes the strategy to bring the electricity market to starkberg equilibrium:

\[ (q_1, q_2) = (q_{wBid,t}, q_{wRT,t}) \]  

(13)

**Conclusion**

Replacing traditional energy sources with renewable energy is an inevitable trend of energy transformation in the future. However, the development of new energy sources such as solar energy, hydropower and biomass is limited by various conditions. Wind power takes up a large proportion of renewable energy sources and increases year by year. The intermittency and randomness of wind power are two major obstacles to its development.

Therefore, this paper puts forward the influence of wind power entering on the balance of power market and the control method: In view of different market rules and conditions: bidding rules, flexible demand, expansion of market capacity, new energy subsidies, fossil fuel energy tax, etc., the power market system operators take appropriate deviation punishment measures to restrain the strategic issuance of wind power manufacturers, so as to ensure the safety and fairness of market operation. It provides valuable reference for making market policy in practical application.

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