Trading mechanism for day-ahead power generation rights considering carbon emission rights and allowance benefits

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Abstract: To improve the enthusiasm of captive power plants to participate in power generation rights trading, this paper proposes a method of power generation rights trading for captive power plants and wind power before the day considering carbon emission rights and allowance gains. Firstly, based on the cooperative game, a power generation rights trading model to maximize the net gain of the cooperative alliance is established, followed by determining the gain of each subject through the Shapley value method. Finally, the model is solved by the solver and the arithmetic example verifies the correctness of the model.

Keywords- Power generation rights trading; carbon emission rights; style; allowance gains; the Shapley

1. Introduction

In the context of new energy vigorously promoted, large-scale wind power grid connection brings challenges to system peaking. Under the new power system, the proportion of coal power is gradually decreasing, and the system regulation capacity is insufficient to meet the requirements of the high proportion of new energy consumption. The utilization hours of enterprise self-provided power plant units are higher than those of the centralized units, which objectively aggravates the pressure of peaking and frequency regulation of public power plants.

To promote the consumption of new energy and accelerate the construction of a power market-based trading mechanism adapted to the consumption of new energy, experts and scholars have researched medium- and long-term and day-ahead power generation rights trading between thermal power and new energy. In the wind-fire medium- and long-term power generation rights trading, the high and low price is used as the priority for "high-low matching" to determine the clearing tariff and traded power [1]. In the literature [2], the external environmental benefits such as energy consumption, sulfur emission, and carbon emission are considered, and the effective value of each index is used as the evaluation criterion of trading priority after combining with the declared tariff. The dispatching department makes generation plans based on the wind-fire medium- and long-term trading power before the day and adjusts generation plans during the day according to the wind resources and load conditions to reduce the pressure on the peaking units[3]. In a short time scale due to the randomness and volatility of renewable energy bringing the most accurate peaking demand, so many scholars have researched day-ahead power generation rights trading, and to stimulate the market players to participate in power generation rights trading. The literature [4] takes into account the trading prices of power generation rights and green certificates and carries out a non-cooperative game with the objective function of maximizing the respective benefits of captive thermal power plants and PV. The literature [5] allocates the incremental revenue from the marginal cost of new energy generation lower than that of thermal power generation, and the revenue per unit of electricity of the coalition is significantly increased. The analysis shows that the Shapley value allocation strategy is more stable, and the cooperative game can significantly improve the overall economic efficiency of the system and the wind power consumption rate.

In summary, it can be seen that the generation rights trading of captive power plants has a slight surplus of revenue under the existing market model, which limits the enthusiasm of captive power plants to carry out trading. With the development of the carbon market, green power certificate, and quota system, if this part of environmental benefits and coal price changes are considered it can make the resources of both parties optimally allocated under a greater interest drive. To this end, this paper proposes a day-ahead generation rights trading model that takes into account carbon emission rights and allowances, by combining captive power plants and wind farms in the form of a cooperative alliance.

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2. The cooperation game between captive power plants and wind power

2.1 Cooperative game model composition

The cooperative game focuses on collective rationality and investigates how the cooperators generate the maximum cooperative surplus and how the coalition gains are distributed.

Definition: Cooperative game (N, v) N = {1, ..., n}, and the characteristic function v represents the payoff of the cooperative coalition as a whole. The characteristic function v satisfies superadditivity, i.e.

$$v(\{N\}) \geq v(1) + v(\{2,\cdots,n\}) \geq v(1) + v(2) + v(\{3,\cdots,n\}) \geq \cdots \geq \sum_{i=1}^{n} v(i) \tag{1}$$

When the above equation is greater than the relation, it means that the coalition creates a new cooperative surplus and the coalition makes sense, but whether the new coalition can be maintained depends on how the cooperative surplus is distributed [6]. The final n-dimensional real payment vector obtained by each bureaucrat needs to satisfy

1) Holistic rationality: the coalition as a whole plays a game with the out-of-coalition insiders or the coalition for the cooperative surplus to satisfy that the overall payoff is greater than the sum of the payoffs when each member operates individually.

2) Individual rationality: Individuals are willing to join the alliance only if the alliance's allocated revenue is higher than the revenue when operating individually.

2.2 Cooperative game benefit model

2.2.1 Objective function

With the maximum net benefit of the alliance as the objective, the objective function is expressed as the difference between the benefits of the alliance and the benefits of each entity when operating independently, and the mathematical model is expressed as

$$\max R_{\mathrm{n}} = R_{\mathrm{t}} - R_{o} \tag{2}$$

where: R_{n} is the net income of the alliance; R_{t} is the income of the alliance; R_o is the sum of the benefits of all members when operating individually.

The revenue after the cooperative alliance is equal to the sum of wind power feed-in tariff revenue and carbon emission rights revenue minus the cost of buying power from the captive power plant and the energy cost of its power generation.

$$R_{\mathrm{t}} = R_{\mathrm{grid}} + R_{\mathrm{CO_2}} - C_p - C_c \tag{3}$$

Where: R_{grid} is the wind power feed-in revenue; $R_{\mathrm{CO_2}}$ is the carbon emission right revenue; C_p is the power purchase cost of captive power plant feed-in; C_c is the energy cost of captive power plant generation.Among them.

Feed-in power purchase cost of captive power plants C_p and wind power feed-in power revenue R_{grid}

$$C_p = \sum_{t=1}^{T}\sum_{i=1}^{x} Q_{i,t} P_{o,g} \tag{4}$$

Where: x is the number of captive power plants; $Q_{i,t}$ is the traded electricity of the ith captive power plant; $P_{o,g}$ is the feed-in tariff of the captive power plant; T is the trading period.

$$R_{grid} = \sum_{t=1}^{T}\sum_{j=1}^{y} Q_{j,t} P_{o,w} \tag{5}$$

where: y is the number of wind farms; $Q_{j,t}$ is the traded electricity of the jth wind farm; $P_{o,w}$ is the feed-in tariff of wind power.

Operating energy costs of self-provided power plants C_c

In the conventional peaking phase of thermal power units, the thermal peaking energy cost consists of the operating coal consumption cost, which is usually calculated using the consumption characteristics given by the following equation:

$$C_c = \sum_{i=1}^{x}\left(a_i P_{i,t}^2 + b_i P_{i,t} + c_i\right) S_{\mathrm{C}} \tag{6}$$

Where: $P_{i,t}$ is the output value of unit i at time t; S_{C} is the coal price in the current season.

Carbon emission rights revenue $R_{\mathrm{CO_2}}$

In the future, the issuance of carbon emission allowances will gradually transition from gratuitous allocation to auction, therefore, in this paper, it is assumed that each reserve power plant i receives a total amount of carbon allowances M_i, the value of which is equal to the carbon emissions of the captive power plant when it is self-generated and self-used, $R_{\mathrm{C,o}} = 0$

After the cooperative alliance, the carbon emissions of the captive power plants are reduced and the proceeds from the sale of the remaining allowances $R_{\mathrm{CO_2}}$ are as follows.

$$R_{\mathrm{CO_2}} = \sum_{t=1}^{T}\sum_{i=1}^{x} \delta\left(M_i - CO_{2,i,t}\right) \tag{7}$$

$$CO_{2,i,t} = \alpha_i Q_{i,t}^2 + \beta_i Q_{i,t} + \gamma_i \tag{8}$$

Where: α_i, β_i, γ_i are the carbon emission characteristic curve parameters of the ith captive power plant; $CO_{2,i,t}$ is the carbon dioxide emission from the output of captive power plant i at moment t; δ is the unit carbon price.

When not participating in power trading, the captive power plant generates all the electricity for its use, and the cost includes coal consumption, the cost of purchasing allowances, and the cost of carbon emissions; for wind farms, when not participating in power trading, their revenue is zero.

$$R_o = -C_{Coal} - C_{\mathrm{RPS}} + R_{\mathrm{C,o}} + R_{w,o} \tag{9}$$

$$R_{w,o} = 0 \tag{10}$$

where: C_{Coal} is the cost of coal consumption under the original output curve of the captive power plant; C_{RPS} and $R_{\mathrm{C,o}}$, are the cost of allowances and carbon emissions respectively when the captive power plant does not participate in the power trading; $R_{w,o}$ is the benefit of the wind farm when it does not participate in the power trading.

C_{Coal} and $R_{C,o}$ are calculated in the same way as and respectively; the calculation method is shown below.

1) Gain from quota reduction

The captive power plants can complete the new energy consumption quota through renewable energy alternative power generation in the power generation right trading, and reduce the cost expenditure of unfulfilled quota, and the reduced quota cost of power generation right trading is shown in equation (11).

$$C_{\mathrm{RPS}} = \sum_{t=1}^{T}\sum_{i=1}^{x} \lambda_{\mathrm{RPS}} Q_{i,t} / 1000 \tag{11}$$

where: C_{RPS} is the reduced quota cost expenditure; λ_{RPS} is the trading price per unit of excess electricity consumption or green certificate.

2.2.2 Trading constraints for power generation rights

1) Transaction volume constraint

$$Q_{i,t} \le P_{\mathrm{o},i,t} \tag{12}$$

$$\sum_{i=1}^{x} Q_{i,t} \le \sum_{j=1}^{y}\left(\hat{P}_{j,t}^{\mathrm{W}} - P_{j,t}^{\mathrm{W}}\right) \tag{13}$$

Where: $P_{o,\,i,t}$ is the original output of captive power plant i at time t. $\hat{P}_{j,t}^{\mathrm{W}}$ is the day-ahead wind power prediction of the wind farm at time t; $P_{j,t}^{W}$ is the day-ahead dispatch output value of the wind farm at time t.

2) Generator power constraints

$$\begin{cases} P_{i,\min} \le P_{\mathrm{G},i,t} \le P_{i,\max} \\ P_{\mathrm{G},i,t} - P_{\mathrm{G},i,t-1} \le R_i^{\mathrm{up}} \\ P_{\mathrm{G},i,t-1} - P_{\mathrm{G},i,t} \le R_i^{\mathrm{dn}} \end{cases} \tag{14}$$

Where: $P_{i,\ \min}$ are the minimum output of unit i respectively; R_i^{up}, $\mathrm{R}_i^{\mathrm{dn}}$ are the output limits of the upward and downward climbing adjustment of captive power plant i respectively.

2.3 Alliance multi-body benefit distribution

According to the Shapley value theory, the benefit distribution formula is as follows.

$$\begin{cases} x_i = \sum\limits_{S \subset N \setminus \{i\}} W(S)\left[v\left(S \cup \{i\}\right) - v(S)\right] \\ W(S) = \dfrac{|S|!\left(|N| - |S| - 1\right)!}{|N|!} \end{cases} \tag{15}$$

where $|S|$ is the total number of elements of the coalition S; $W(S)$ denotes the weighting factor of the respective coalition, i.e., the allocation factor.

3. Analysis of calculation cases

3.1 Gaming space

With the predicted wind power output known, the dispatched output of wind power in the results of the day-ahead unit combination can be obtained. From Figure 1, it can be seen that wind abandonment exists for t=1~11 and 21~24.

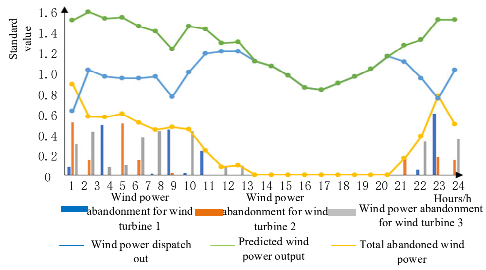

Fig.1 Wind power forecast output and unit combination model to dispatch wind power output

3.2 Cooperative game solving results

The time of the day with the most abandoned wind power is selected for analysis, i.e., at t=23, there is still 219 MW of abandoned wind power not consumed by thermal power units.

Tab.1 Cooperation game each subject trading power

Wind power trading power (MW)			Captive power plant trading power (MW)		
Wind turbine 1	Wind turbine 2	Wind turbine 3	Captive power plant 1	Captive power plant 2	Captive power plant 3
176.0	43.0	0.0	76.0	70.5	72.5

From Table 1, it can be seen that the power traded among the power generation rights trading offerors in descending order is captive power plant 1, captive power plant 3, and captive power plant 2. The original output of captive power plant 1 is higher than that of captive power plants 2 and 3, and the range of output that can be reduced is larger, thus the power traded is the largest.

When the captive power plants in the cooperative alliance can fully consume the abandoned wind power, the amount of traded power is related to the planned power output of the original captive power plant and the revenue per unit of power output reduction when participating in the power trading, and the power plant with higher net revenue per unit of power output reduction will be given priority.

3.3 Profit distribution

Tab.2 Revenue allocation among captive power plants and wind farms

Trading Subjects	Revenue / million
Wind turbine 1	7.27
Wind turbine 2	2.08
Captive power plant 1	3.12
Captive power plant 2	2.97
Captive power plant 3	3.83

As can be seen from Table 2, the contribution of the same type of subject in the alliance is reflected in the form of trading electricity into the power among the power generation rights trading cedants.

4. Conclusion

In this paper, we propose a method for trading power generation rights of captive power plants and wind farms considering carbon emission rights and allowance gains before and after the existing power market mechanism with a large trading space. Based on the cooperative game theory, the optimization model of the number of trading subjects and trading power is established to maximize the difference between the benefits before and after the trading of power generation rights, and the total benefits of the alliance are allocated by using the improved Shapley value, and the correctness of the model is verified by the calculation examples.

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