Operation Decision Model of Wind-Photovoltaic-Storage Hybrid Power System in the Day Ahead Market

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Abstract. In this paper, considering the uncertainty of electricity price and the uncertainty of wind power generation and photovoltaic power generation in the day ahead electricity market, a bidding decision-making model of wind solar energy storage complementary power system composed of wind turbine, photovoltaic generator set and energy storage system is constructed by using two-stage stochastic programming method, so as to maximize the interests of system operators. Finally, the rationality of the model is proved by an example.

1. Introduction

With the continuous development of the power market, the power market has entered the application stage. The 13th five year plan further points out that the spot trading market will be fully launched in 2020. With the development of electricity spot market, each generating unit needs to be connected to the Internet through bidding. Adding energy storage device on the basis of wind and photovoltaic complementary improves the power output characteristics of the whole wind solar power generation system to a certain extent. However, compared with the traditional fossil fuel power generation, the wind solar storage hybrid power system still has more uncertainties. By studying the joint operation characteristics of wind photovoltaic storage hybrid power system, an optimal bidding strategy for day ahead power market is established, which is of great significance for wind photovoltaic storage hybrid power system to participate in power market transactions.

System operators need to consider the joint operation of their wind photovoltaic storage complementary system to optimize the optimal bidding strategy in day ahead power market. However, due to the intermittence and fluctuation of wind speed and solar radiation intensity, the unit output level is uncertain. Moreover, the price fluctuation and energy balance are also uncertain. Therefore, system operators must consider these uncertainties in order to obtain stable returns from the electricity market.

To sum up, considering the above uncertainties, in view of the joint operation of photovoltaic power generation system with energy storage device and wind power generation system, it is necessary to propose an optimal bidding scheme for day ahead power market to ensure its revenue. However, at present, most of the researches on the operation of the combined system at home and abroad focus on the optimal dispatch of uncertain unit output, without considering the uncertain fluctuation of electricity market price. Therefore, considering the double uncertainty of unit output and market price faced by system operators, this paper adopts two-stage stochastic programming method to solve the problem. In the first stage, the uncertainty of renewable energy output is not considered in this stage. Bidding decision is made on the basis of wind power forecast output and electricity market price forecast. In the second stage, considering the uncertainty of wind turbine output in real-time operation, the decision
optimization is carried out according to the decision-making joint energy storage system in the previous stage, and the power deviation of unit output is compensated by unbalanced market power.

2. Operation decision model of wind solar storage hybrid power system

Considering the energy imbalance and price imbalance faced by system operators, the problem is described as a two-stage stochastic optimization problem. The optimal bidding scheme is determined by mixed integer linear programming, which assumes that the processing level of wind power and photovoltaic power generation is random, and the model is built through the basic scenario. Set these scenes as collections That is, the scene set of 24 hours the next day, and each scene From the probability of occurrence weighting.

(1) Objective function

The objective function of wind solar storage hybrid power system is to maximize the revenue. The objective function is as follows:

\[
\sum_{i=1}^{\Omega} \sum_{t=1}^{T} \pi_i (p_{i,t}^D P_t + p_{i,t}^D r_{i,t}^+ \Delta_{i,t}^+ - p_{i,t}^D r_{i,t}^- \Delta_{i,t}^-)
\]  

(1)

(2) Constraints

1) Equipment output constraints:

\[
0 \leq P_t^W \leq P_{W_{max}}, \forall t
\]  

(2)

\[
0 \leq P_t^{PV} \leq P_{PV_{max}}, \forall t
\]  

(3)

\[
0 \leq P_t \leq P_{W_{max}} + P_{PV_{max}} + P_{t_{Debat}}
\]  

(4)

Where, \( P_t^W \) is the wind power output in t period, \( P_t^{PV} \) is the photovoltaic output in t period, \( P_{W_{max}} \) is the maximum power of the wind system, \( P_{PV_{max}} \) is the maximum power of photovoltaic system, \( P_{t_{Debat}} \) is the discharge power of the energy storage device.

2) Output power imbalance constraints

The output power of wind power, photovoltaic and energy storage combined device is as follows:

\[
P_{t_{so}} = P_{t_{so}}^W + P_{t_{so}}^{PV} - P_{t_{Chbat}}^t + P_{t_{Debat}}
\]  

(5)

Where \( P_{t_{so}}^W \), \( P_{t_{so}}^{PV} \), \( P_{t_{so}}^{Chbat} \), \( P_{t_{Debat}} \) are respectively system output power, wind power output power, photovoltaic power output power, energy storage system charging power and energy storage system discharging power of the scene under the time period.

\[
\Delta_{t_{so}} = P_{t_{so}} - P_t, \forall t, \forall \omega
\]  

(6)

\[
\Delta_{t_{so}} = \Delta_{t_{so}}^+ - \Delta_{t_{so}}^-, \forall t, \forall \omega
\]  

(7)

\[
0 \leq \Delta_{t_{so}}^+ \leq \Delta_{t_{so}}^- \leq P_{t_{so}} + u_{t_{so}}(1 - u_{t_{so}}), \forall t, \forall \omega
\]  

(8)

\[
0 \leq \Delta_{t_{so}}^- \leq (P_{W_{max}} + P_{PV_{max}} + P_{t_{Debat}})(1 - u_{t_{so}}), \forall t, \forall \omega
\]  

(9)

Where, \( \Delta_{t_{so}} \) is the total energy deviation of the scene \( \omega \) of the complementary power system under t time period, and \( \Delta_{t_{so}}^+ \), \( \Delta_{t_{so}}^- \) are respectively the positive and negative energy deviation of the scene \( \omega \) under t time period, \( u_{t_{so}} \) is 0/1 variable. When the positive energy deviation occurs, it is equal to 1; otherwise, it is equal to 0.
Energy storage system constraints
The operation state of energy storage system is as follows:

\[ E_{t}^{bat} = E_{t-1}^{bat} + \eta_{Chbat} P_{t}^{Chbat} - \frac{1}{\eta_{Debat}} P_{t}^{Debat} \]  

(10)

Where, \( E_{t}^{bat} \) is the energy stored in the energy storage device during \( t \) period, \( \eta_{Chbat} \) is the charging efficiency of the energy storage device, \( \eta_{Debat} \) is the discharge efficiency of the energy storage device.

The capacity constraints of the energy storage system are as follows:

\[ 0 \leq E_{t}^{bat} \leq E_{batmax}^{max} \]  

(11)

Where, \( E_{batmax}^{max} \) is the maximum capacity of the energy storage device.

The state constraints of energy storage system are as follows:

\[ 0 \leq P_{t}^{Chbat} \leq P_{t}^{Chbatmax} k_{i} \]  

\[ 0 \leq P_{t}^{Debat} \leq P_{t}^{Debatmax} (1 - k_{i}) \]  

(12) \hspace{1cm} (13)

Where, if the energy storage device is in charging state in hour \( T \), it is equal to 1; otherwise, if the energy storage device is in discharge state, it is equal to 0.

3. Model Solving Algorithm
Considering the two kinds of uncertainties in the operation of wind solar storage hybrid power system, this paper uses a two-stage stochastic programming algorithm to solve the model. The objective function of two-stage stochastic programming is as follows:

\[ \max c^{T} x + E[\max \{ y_{\omega}^{T} q_{\omega}^{T} y_{\omega} \}] \]  

(14)

The constraints are as follows:

\[ b \leq Ax \leq \bar{b} \]  

(15)

\[ h_{\omega} \leq T_{\omega} x + W_{\omega} y_{\omega} \leq \bar{h}_{\omega}, \forall \omega \]  

(16)

\[ x \geq 0, y_{\omega} \geq 0, \forall \omega \]  

(17)

Where, \( c \) is the coefficient vector of the \( x \) variable in the first stage known to the objective function, \( x \) and \( y_{\omega} \) are the variables in the first and second stages respectively, and \( q_{\omega} \) is the coefficient vectors of the constraints in the first stage. \( b \) and \( \bar{b} \) are the lower bound and upper bound of the constraint in the first stage, and vector \( A \) is the known constraint coefficient matrix of the stage. \( h_{\omega} \) and \( \bar{h}_{\omega} \) are the lower bound and upper bound of the constraint in the second stage, respectively. \( T_{\omega} \) is the technical matrix, \( W_{\omega} \) is the resource matrix. The two-stage stochastic programming problems derived from (13)-(16) can be equivalently expressed as deterministic programming problems, as shown below:

\[ \max x, y_{\omega} \quad c^{T} x + \sum_{\omega} \rho_{\omega} q_{\omega}^{T} y_{\omega} \]  

(18)

The constraints are as follows:
\[ b \leq A x \leq \bar{b} \]  
\[ h^T x + W_{x,\omega} \leq \bar{h} \omega, \forall \omega \]  
\[ x \geq 0, y_{\omega} \geq 0, \forall \omega \]  

4. Example Analysis

The day ahead market data is obtained from the average processing of historical data of a certain region in a certain 10 days in the statistical period. The system operators bid by hour in the daytime market. The installed capacity of wind power system and photovoltaic power generation system is 300MW, and the capacity of energy storage system is 137mw. The charging and discharging efficiency of energy storage equipment is 80% and 95% respectively. According to the day ahead market price of these 10 days, the average price curve of day ahead market is shown in Figure 1.

As shown in Figure 1, the highest average market price appears around 13 hours, which is 600 yuan / MWh. At the same time, the lowest average price is 450 yuan / MWh, and the average price of discharge of energy storage equipment is expected to be 590 yuan / MWh. The average output of wind turbines and photovoltaic generators is obtained by taking 10 days' historical data in the statistical period, as shown in Fig. 2.

The wind, Photovoltaic and storage complementary system shall be bid jointly. By using the above data and formulas (1) - (21), and solving by gams / CPLEX, the results shown in Fig. 3 can be obtained.
Electricity trading volume (MWh)

Time (h)

0 80 160 240 320 400 480

After optimization
Not optimized

Figure 3. Best bidding power curve of system operators in day ahead Market

Figure 3 shows that the non optimized strategy can conduct more bidding between 11h and 15h, but if the actual power generation is less than the transaction volume in the day ahead market, the system operators will bear the negative unbalanced loss, that is, they need to pay compensation higher than the market price to the day ahead market. Considering the fluctuation of day ahead market price and unbalanced price, the optimized bidding strategy chooses the appropriate bidding between 11h and 15h.

The charging and discharging strategy of the energy storage system and the electricity market price are shown in Figure 4. The charging and discharging operation of the energy storage system is conducive to obtaining the best bidding strategy. According to the change trend of electricity market price, the energy storage device charges within 4 hours to 5 hours when the price is low, and discharges when the energy is maintained to 13 hours.

Figure 4. Charging and discharging power curve of energy storage system

The final results are as shown in Table 1. The expected trading energy and total expected profit of no optimized bidding are 4984mwh and 2492000 yuan respectively, while those with optimized bidding are 4732mwh and 2602600 yuan respectively. Therefore, although the expected energy of the transaction is reduced by 252mwh, the profit after optimization is increased by about 110600 yuan, that is, the daily profit increases by about 4.4%.

Table 1. Electricity trading volume and income statement of system operators

|                  | Trading volume (MWh) | Income (yuan) |
|------------------|----------------------|---------------|
| Not optimized    | 4984                 | 2492000       |
| After optimization | 4732                | 2602600       |
Finally, the scenario simulation is carried out: wind power generation fluctuation, photovoltaic power generation adopts average value to eliminate its uncertainty (blue); photovoltaic power generation fluctuation, wind power generation adopts average value to eliminate its uncertainty (green); wind power generation and photovoltaic power generation maintain fluctuation (brown). As shown in Figure 5.

![Figure 5. System operation best bidding power](image)

It can be seen from Figure 5 that the transaction volume represented by blue and Brown is selected for comparison. From 11h to 16h and 18h to 20h, the Photovoltaic intensity is large. Without considering the fluctuation from photovoltaic, selecting high-power photovoltaic power generation system for power market bidding can effectively reduce the loss caused by negative power imbalance. In 0h-5h and 20h-24h, the trading volume shown in blue and Brown is the same because photovoltaic power generation is zero at this time, and there is no influence of photovoltaic fluctuation. By comparing the green and brown bids, it is found that all hours except 12h to 14h and 19h without considering the fluctuation of wind power are conducive to the bidding of high-power wind power generation system in the electricity market. The exception is in 13 hours. At this time, although there may be negative power imbalance, due to the high market price in the day ahead, it is still advantageous to adopt the discharge of energy storage system.

Finally, it can be concluded that the uncertainty and volatility of wind power generation in the actual output situation can be dealt with by unbalanced price ratio to determine the optimal bidding power; and the uncertainty of wind power output has a greater impact on the bidding strategy than the uncertainty of market price in the day ahead.

5. Summary
In this paper, based on the uncertainty of power market and wind and Photovoltaic output, the bidding strategy of power system operators is optimized in the day ahead electricity market bidding environment, and the electricity bidding problem of wind photovoltaic storage complementary power system operators in day ahead market is solved.

The simulation results show that this optimization method can reduce some bidding power in day ahead market, reduce the loss when the power is unbalanced, and increase the revenue. At the same time, the uncertainty of the actual output of the generation system has a greater impact on the bidding strategy than the uncertainty of the day ahead market price.

Acknowledgements
The work described in this paper was supported by the science and technology project of State Grid Corporation of China (SGQHDKY0DWJS1800170, Research and application of key technologies of Wind power - photovoltaic - energy storage integrated optimization demonstration).
References

[1]. Chen Jinbao, Wang Yameng. Study on the combined utilization system of water, wind, and energy [J]. Technology and market, 2020, 27 (01): 62-63

[2]. Li Yan, Peng Yaohong, Cui Hanjun. Development and key technologies of multi energy complementary power generation [J]. Shaanxi water conservancy, 2019 (12): 26-28

[3]. Zhang xincapsule, Huang Weibin, Wang Feng, Ma Guangwen, Chen Shijun. Study on optimal operation of large-scale wind solar hybrid energy complementary power generation system [J]. China Rural Water Conservancy and hydropower, 2019 (12): 181-185 + 190

[4]. Xiao Ping. Discussion on site selection of photovoltaic power station by using analysis method [J]. China electric power industry (technical Edition), 2014, 06:61-64

[5]. Zhang Li, Gao Yuanhai, Xiong Ning, Wang Chun, Yang Cong, Shu Jiao. Site selection and sizing planning of distributed photovoltaic power stations considering the constraint of power flow reversal [J]. Power system automation, 2014, 17:43-48

[6]. Erdinc O, Elma O, Uzunoglu M, et al. Real-time performance analysis of an optimally sized hybrid renewable energy conversion unit[J]. Energy and Buildings, 2014, 75(jun.): 419-429.

[7]. Kresnawan M R, Setiawan A A, Wilopo W. Optimal Sizing Scenario of Hybrid Wind-PV Energy in Coastal Road Balikpapan[C]// Regional Conference on Chemical Engineering. 2018.

[8]. Hammoumi K E, Bachtiri R E, Boussetta M, et al. Dimensioning of a battery system to store energy from a hybrid PV/wind/diesel system at 3 kVA[J]. IOP Conference Series Earth and Environmental ence, 2018, 161(1):012011.