Bidding strategy of wind-solar hybrid generation system in the spot market considering bidding deviation penalty

Daning You¹, Hanghang Liu², Juncheng Si², Lei Zhou¹, Mingyu Sun² and Ting Jiang³

¹State Grid Shandong Electric Power Company, Jinan, Shandong, 250001, China
²Dongying Power Supply Company of State Grid Shandong Electric Power Company, Dongying, Shandong, 257000, China
³School of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China

*Corresponding author’s e-mail: jtjt9898@sjtu.edu.cn

Abstract. In recent years, as State Grid Shandong Electric Power Company is one of the key pilot construction units of the new strategy of "realizing the coordination and interaction of source network, load and storage", renewable energy power generation systems have gradually changed from a subsidy object to an independent bidding subject when participating in the spot power market of Shandong Province. The uncertainty of renewable energy output and spot market price leads to the loss caused by bidding deviation when participating in the power market competition, and the income drops significantly. The good complementarity of wind and solar energy can reduce the fluctuation of renewable energy output and promote renewable energy consumption. First, the joint output probability distribution of a wind-solar hybrid generation system is simulated based on Copula function. Then, aimed at maximizing the bidding profit of the wind-solar hybrid generation system in spot market, a two-stage mixed integer stochastic optimization bidding model considering bidding deviation penalty is established. The conditional value at risk theory is used to evaluate the risk of renewable energy and electricity price forecast deviation, and the optimal bidding strategy is obtained.

1. Introduction
In 2020, the change of power supply structure in Shandong Province will accumulate from quantitative change to the key node of qualitative change, and the installed capacity of renewable energy in Shandong Province will increase rapidly. Due to the great uncertainty of renewable energy in the existing power market, China mainly supports its development by setting price subsidy mechanism. Renewable energy units do not bid, which greatly restricts its future development. With the progress of wind energy and solar energy technology, they become more and more competitive, and subsidies will be greatly reduced or even stopped. China's provinces are actively formulating detailed market rules for wind power bidding. Shandong Provincial Energy Bureau has issued the notice on doing a good job in the province's power market trading in 2021. The notice proposes that from 2021, the qualified centralized new energy power generation enterprises should be encouraged to enter the power market to participate in the trading, and the new energy enterprises that have signed the market trading contract should be in the power grid peak shaving hard time period is given priority. This is a sign of the future trend of photovoltaic and wind power market competition. Therefore, wind-
solar hybrid generation system needs to formulate appropriate strategies to participate in the power market and maximize its profit.

In the spot electricity market, the independent system operator (ISO) will impose unbalanced penalties on the generators who do not meet the production plan[2]. Due to the high uncertainty of wind and solar energy day ahead forecast, price fluctuation and deviation penalty cost, wind-solar hybrid generation system is faced with high risks, it is necessary to avoid the risks brought by these three uncertainties. For this reason, reference [3] establishes the optimal bidding strategy model of wind power through stochastic programming, and introduces the bilateral reserve market mechanism, which makes wind power suppliers benefit from purchasing cheap reserve power, but increases the real-time market competition and scheduling pressure. In order to reduce the risk of wind power curtailment and power rationing caused by the uncertainty of wind turbine output, based on the probability sequence theory, the uncertain optimization problem was transformed into the deterministic optimization problem in [4], and the multi-objective optimal scheduling scheme of wind fire joint was obtained. The relationship between demand response and wind power output is considered from the perspective of electricity price, and it is introduced into the optimal dispatching model of wind power system, which provides an effective method to promote the high proportion of renewable energy consumption. Multi energy cooperative bidding increases the scale of power generation system, which is beneficial to stabilize the risk of distributed energy and obtain excess profits. However, the current research on photovoltaic power generation participating in the electricity market bidding is relatively less, and more research focuses on the photovoltaic power station grid connection problem and control strategy[7]. How to improve the economy of wind photovoltaic hybrid generation system to participate in the spot market is a problem to be solved.

This paper studies the strategy of bidding for a wind-solar hybrid generation system to participate in spot market. First, a two-stage mixed integer stochastic programming mathematical model of the wind-solar hybrid generation system participating in spot market operation optimization is established. CVaR is adopted to deal with the uncertainties of wind and solar power output, price fluctuation and deviation penalty cost. Finally, the effectiveness of the proposed bidding strategy is verified by a case study. The proposed method can help decision makers to get the best balance between the expected profit and risk.

2. Joint output probability distribution of wind-solar hybrid generation system based on Copula function

The output of the wind-solar hybrid generation system includes two parts: wind turbine output and solar plant output. In the actual operation, the output of wind-solar hybrid generation system in different locations and different periods is very complex. Based on this, it is necessary to study the joint probability distribution of the output of wind-solar hybrid generation system. However, the output of wind and solar power stations are nonlinear functions. The traditional correlation coefficient method cannot be used to characterize the correlation of the nonlinear distribution, because the nonlinear distribution does not necessarily have expectation and variance, and the correlation coefficient theory is based on the expectation and variance theory. Moreover, in engineering, it is not necessary to regard the wind and solar output as a continuous function, and simplifying it as a discrete distribution is more conducive to engineering application and can greatly reduce the amount of calculation. Therefore, this paper proposes a method to solve the joint probability distribution of wind and solar power output, based on Copula function to obtain the joint probability distribution function of wind and solar power output. It is more complex to determine the joint probability distribution of the two through the traditional probability theory, and copula theory is a theory to solve the complex high-dimensional joint probability distribution.

Copula functions are mainly divided into elliptic Copula functions and Archimedean Copula
functions, where Archimedean Copula functions are most widely used. They can be described as (1).

\[
C_u(u_1, u_2, \cdots, u_d) = \phi^{-1}\left(\left[(-\log u_1)^{\psi\theta} + (-\log u_2)^{\psi\theta} + \cdots + (-\log u_d)^{\psi\theta}\right]^{1/\psi}\right)
\]  

(1)

where \( \theta \) is the parameter of Copula function.

3. Bidding model for wind-solar hybrid generation system

According to the power market rules of Shandong Province, the power market is composed of day ahead market and real-time market. The day ahead market can ensure that the day ahead market trading power of market members is settled at the day ahead price, and only the deviation between the real-time and the day ahead is exposed in the real-time price. This paper studies the two-stage operation mode of the wind-solar hybrid generation system participating in day ahead electricity market and real-time equilibrium market, as shown in figure 1. According to the forecast of wind and solar power output and electricity prices, the wind-solar hybrid generation system submits the quotation curve on the day before the operation day. In actual operation, due to the existence of prediction error, the actual output of the system will deviate from the day ahead plan, and the system needs to bear the financial risk caused by the generation deviation in the real-time market. Considering that the bidding mechanism of wind power market in Shandong Province is still not perfect, to prevent the wind-solar hybrid generation system from deliberately reducing the bidding volume in the day ahead market to avoid the loss of high purchase price in case of power shortage, the two-price method is adopted to promote its reasonable bidding[8]. It means that when there is a positive or negative unbalanced electricity price, different real-time electricity prices are adopted to clear the market[9]. There is no arbitrage space, which is conducive to enhancing the enthusiasm of market players.

![Figure 1. Operation mode of wind-solar hybrid generation system in spot market](image)

3.1. Objective function

As the proportion of renewable energy generation in power system is still low, this paper considers that it is a price taker in the spot market, that is, its market behaviors will not affect the day-ahead and real-time prices. Due to uncertain factors such as wind turbine output and electricity prices, the actual output of the system may not be consistent with the submission. The deviation power will be traded by ISO in the real-time balance market. The purpose of the wind-solar hybrid generation system participating in the spot market is to maximize the operation income, so the profit is equal to income minus cost. The objective function is shown in (2), including wind turbine income \( R_{\text{wind}} \), solar plant income \( R_{\text{solar}} \) and unbalanced income \( R_{\text{imb}} \).

\[
\max \sum_{\omega=1}^{\Omega} \pi_{\omega} \left( R_{\text{wind}} + R_{\text{solar}} + R_{\text{imb}} \right)
\]  

(2)

where \( \pi_{\omega} \) is the probability of scenario \( \omega \).
\[ R_{\text{wind}} = \sum_{n=1}^{N} \sum_{\omega} \lambda_{n,\omega} W_{t,n,\omega}, \forall \omega \]  
(3)

where \( \lambda_{n,\omega} \) is the stochastic variable, price, at \( t \) and \( \omega \). \( W_{t,n,\omega} \) is the bidding quantity of wind turbine \( n \) at \( t \) and \( \omega \).

\[ R_{\text{solar}} = \sum_{n=1}^{N} \sum_{\omega} \lambda_{m,\omega} S_{t,m,\omega}, \forall \omega \]  
(4)

where \( S_{t,m,\omega} \) is the bidding quantity of solar plant \( m \) at \( t \) and \( \omega \).

\[ R_{\text{imb}} = \sum_{n=1}^{N} \sum_{\omega} \tilde{\lambda}_{t,n,\omega} \delta_{t,n,\omega} - \tilde{\lambda}_{t,m,\omega} \delta_{t,m,\omega}, \forall \omega \]  
(5)

where \( \tilde{\lambda}_{t,n,\omega} \) and \( \tilde{\lambda}_{t,m,\omega} \) are stochastic variables of up and down regulation prices, respectively. \( \delta_{t,n,\omega} \) and \( \delta_{t,m,\omega} \) are stochastic variables of up and down regulation power, respectively.

3.2. Constraints
- Constraints of wind and solar units
  For wind turbine \( n \), its output should be no more than its rated power \( W_{\text{max},n} \), as (6) shows. The same holds for the solar plant.

\[ 0 \leq W_{t,n,\omega} \leq W_{\text{max},n} \]  
(6)

- Constraints of imbalance power
  To ensure the linearity of the model and avoid introducing auxiliary 0/1 variables, the method of [10] is used to express the positive and negative unbalanced power constraints, as shown in (7)-(9).

\[ \tilde{\lambda}_{t,n,\omega} - \tilde{\lambda}_{t,m,\omega} = \sum_{n=1}^{N} (W_{t,n,\omega} - W_{\text{real},n}) + \sum_{n=1}^{M} (S_{t,m,\omega} - S_{\text{real},m}) \]  
(7)

\[ 0 \leq \tilde{\lambda}_{t,n,\omega} \leq \sum_{n=1}^{N} W_{\text{real},n} + \sum_{m=1}^{M} S_{\text{real},m}, \forall t, \omega \]  
(8)

\[ 0 \leq \tilde{\lambda}_{t,m,\omega} \leq \sum_{n=1}^{N} W_{\text{real},n} + \sum_{m=1}^{M} S_{\text{real},m}, \forall t, \omega \]  
(9)

where \( W_{t,n,\omega} \) is the real output of wind turbine \( n \) at \( t \) and \( \omega \). \( S_{\text{real},m} \) is the real output of solar plant \( m \) at \( t \) and \( \omega \).

- Constraints of bidding curve
  In most markets, it is required that the price volume curve declared by power suppliers should be non-decreasing sequence. Therefore, for the wind-solar hybrid generation system, the bidding curve constraints can be expressed as equations (10)-(11) respectively.

\[ (\lambda_{t,n,\omega} - \lambda_{t,n,\omega'}) (P_{t,m,n} - P_{t,m,n'}) \geq 0, \forall t, \omega, \omega' \]  
(10)

\[ (\lambda_{t,m,\omega} - \lambda_{t,m,\omega'}) (W_{t,n,m} - W_{t,n,m'}) \geq 0, \forall t, \omega, \omega' \]  
(11)

where \( \omega \) and \( \omega' \) are two different scenarios.

3.3. Theory of CVaR and its constraints
The value at risk (VaR) \( \xi \) represents the maximum possible risk of the bidding strategy with the wind-solar hybrid generation system due to the uncertainties under a certain confidence level \( \alpha \). CVaR overcomes the defects of VaR in the consistency of risk measurement. The uncertainties of wind and
solar power output and electricity price can be described by scenarios, so the CVaR based stochastic optimization method is adopted. CVaR and its constraints can be expressed as follows.

\[
\max_{\omega} \sum_{\alpha=1}^{\Omega} \pi_\alpha \left( R_{\text{wind}} + R_{\text{solar}} + R_{\text{imb}} \right) + \beta \cdot R_{\text{CVaR}}
\]

\[
R_{\text{CVaR}} = \xi - \frac{1}{1-\alpha} \sum_{\alpha=1}^{\Omega} \pi_\alpha \eta_\alpha
\]

\[-(R_{\text{wind}} + R_{\text{solar}} + R_{\text{imb}}) + \xi - \eta_\alpha \leq 0, \forall \omega
\]

\[
\eta_\omega \geq 0, \forall \omega
\]

where \( \beta (\beta \geq 0) \) is the risk preference coefficient. As \( \beta \) increases, the system dislikes risk more, and its strategy is more conservative. \( R_{\text{CVaR}} \) is CVaR. \( \eta_\alpha \) is the total profits minus \( \xi \) at scenario \( \omega \).

4. Case study
Based on the above analysis, the calculation process of the model can be divided into three steps: uncertainty scenario generation, spot market bidding strategy formation and expected income calculation. The model can be solved quickly by calling Gurobi 9.0 by MATLAB R2019b and Yalmip.

The installed capacity of the wind farm and the solar plant are 370 MW and 340 MW, respectively. Scenarios are generated by Monte-Carlo sampling method, and reduced by clustering method. Finally, 10 typical scenarios are obtained, as shown in figure 2 and 3. Scenarios of the output of the solar plant and real-time market prices can be obtained in the same way.

When \( \beta > 0 \) wind-solar hybrid generation system is risk averse, and their bidding strategies were relatively conservative. In order to compare the impact of different risk preference coefficient \( \beta \) on the revenue of the wind-solar hybrid generation system, the total income and CVaR under different risk preference coefficients are given in figure 4. It can be seen that with the increase of \( \beta \), the expected
total profits and CVaR show a decreasing trend. In general, when $\beta$ is small or large, the increase of the alliance's expected total income is large, because: in the first case, the value at risk is more sensitive to $\beta$; in the second case, the difference between the income and the value at risk is more sensitive to $\beta$. In addition, when $\beta$ is big, CVaR will increase rapidly with the increase of $\beta$. This shows that in order to obtain greater economic benefits, the wind-solar hybrid generation system should not pursue small probability benefits too much, but should avoid risks as much as possible.

5. Conclusion

In view of the lack of optimal operation strategy for wind-solar hybrid generation systems to participate in spot market in Shandong Province at the initial stage of bidding mechanism construction, this paper proposes optimal operation strategy and revenue distribution model for a wind-solar hybrid generation system to participate in spot market based on conditional value at risk. Uncertainties of wind, solar output and electricity prices will lead the system to face greater risks in the real-time market. The conditional value at risk theory can effectively achieve risk aversion and choose the degree of risk aversion. The results can provide theoretical support for the decision-making of wind-solar hybrid generation systems participating in the spot market.

Acknowledgments

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