Low-carbon Dispatch of Power Systems Based on Wind Power Output Volatility

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Abstract. To investigate the economic impact of wind power output volatility on the operation of power systems, this study constructs a low-carbon dispatch model for power systems that takes into account the volatility of wind power output. By setting different levels of volatility to alter the wind power output, the study ultimately examines the influence of wind power volatility on the overall cost and carbon emission cost of the system. The experimental results indicate that as wind power volatility increases, the on-off states of conventional power generation units change. This not only affects the secure and stable operation of the power system but also leads to increased start-up and shutdown costs for the units, along with an increase in carbon emission costs. Consequently, the total system cost rises, impacting the economic efficiency of system operation. Therefore, in future research, measures should be taken to reduce the numerical value of wind power volatility in order to reduce overall costs and improve the economic efficiency of system operation.

Keywords.Low-carbon dispatch; volatility; electricity market; generation costs

1. Introduction

The inevitable trend in the development of the power industry involves energy conservation, emission reduction, and the vigorous development of new energy sources such as wind power. However, electricity generation from sources like wind power is characterized by volatility, introducing significant safety risks to the stable operation of the system due to its inherent uncertainty. Unlike traditional thermal power generation, wind power integrated into the grid lacks stability and dispatchability. In order to ensure the secure and stable operation of the grid, there may be unavoidable instances of wind power curtailment. Moreover, the random and highly volatile nature of wind power not only exacerbates the peak load pressure on the grid but also significantly increases the standby capacity burden on thermal power units. This not only limits the system's capability to control carbon emissions but also greatly diminishes the economic viability of integrating wind power into the grid. Consequently, the uncertainty associated with

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wind power systems becomes a crucial factor that dispatch decision-makers must consider. Analyzing the impact of wind power output volatility on low-carbon dispatch in power systems is essential for enhancing the economic efficiency of power system operation in the face of uncertainties associated with wind power generation.

In the context of the dual carbon goals, incorporating carbon emissions into a power system with large-scale wind power can reduce the output of thermal power units and decrease the overall carbon emissions of the system. Undoubtedly, the introduction of carbon emissions increases the integration and absorption capacity of wind power into the grid. However, the volatility and uncertainty associated with wind power pose more significant challenges for dispatch decision-making.

Currently, there have been significant achievements in research related to the volatility and uncertainty of wind power. Reference [1] proposed a wind farm output volatility full probability model considering the output level. This model was applied in the economic evaluation of large-scale wind power integration, achieving a more accurate quantitative analysis. Reference [2] conducted an analysis of wind power uncertainty factors and the impact of wind power uncertainty on the power system, addressing key technical issues in wind power uncertainty research and analysis. It serves as a valuable reference for guidance and inspiration. Reference [3] introduced a carpet-type economic dispatch model considering the uncertainty of wind power and load. This model takes into account carbon emission costs, operating costs, and uncertainties, aiming to increase the integration capacity of wind power and other new energy sources while reducing carbon emissions. Reference [4] proposed an economic dispatch method for power systems considering the complementary low-carbon characteristics of sources and loads. This method effectively optimizes resources on both sides of generation and demand, enhancing the system's wind power integration capacity, operational efficiency, and achieving low-carbon emissions. Reference [5] constructed a low-carbon economic dispatch model for a wind-solar-pumped storage system considering the uncertainty of sources and loads. Addressing uncertainties in wind power, photovoltaic power, and load forecasts, the model transformed stochastic chance-constrained programming into a deterministic model. It introduced a penalty-based carbon trading mechanism into traditional economic dispatch, comprehensively considering the system's operating costs and safety and stability. Reference [8] took into account the uncertainty of wind power generation, balancing conflicting objectives and proposing a new method for estimating the uncertainty set of wind power generation.

To summarize, previous researchers have predominantly concentrated on assessing the influence of wind power volatility and uncertainty on the secure and steady operation of power systems following the integration of wind power[6-7]. They have also delved into methods to enhance the grid integration capacity of wind power and other renewable sources. In contrast, this study seeks to fill these gaps by constructing a low-carbon dispatch model for power systems that takes into account the unpredictability of wind power output[9-11]. By introducing various levels of volatility to modify wind power output, the study ultimately examines how wind power volatility affects the overall cost and carbon emission cost of the system. The objective is to offer theoretical insights and decision-making support for enhancing the economic efficiency of power system operation.

2.Research on the settlement model

This paper tackles a common mixed-integer programming issue. It achieves this by taking a comprehensive approach that incorporates variable costs, operating costs, and carbon emission costs associated with traditional power generators, alongside accounting for the influence of wind power output volatility. The result is the development of a low-carbon dispatch model for power systems. The primary objective of this model is to minimize the overall cost of the power system while adhering to specific constraints. In the course of optimizing this model, the study delves into an analysis of how different levels of wind power volatility impact both the overall cost and carbon emission cost of the system.

2.1.The Low-Carbon Dispatch Model for Power Systems Considering Wind Power Output Volatility

The market optimization model adopts a unilateral bidding mechanism in the power generation sector. The following model aims to minimize operational and startup costs to the greatest extent possible. Simultaneously, this model is based on a given load curve (e.g., the load for each hour within a day) and a specified set of available generating units, determining when to start and stop units and how much electricity to generate to economically meet the load demand. The objective function is as follows,

$$minF = \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{t=1}^{T} \left(C_{i,0,t} u_{i,t} + S_i y_{i,t} + c_{i,b,t} P_{i,b,t}\right) \tag{1}$$

Where,

i represents the unit index; b represents the segment index; t represents the time period index;

I represents the total number of units;

B represents the number of segments;

T represents the number of time periods;

$C_{i,0,t}$ represents the cost at the minimum output for unit i in time period t;

$P_{i,b,t}$ represents the output of unit i in segment b and time period t, which is the variable to be optimized;

$c_{i,b,t}$ represents the marginal cost of unit i in segment b and time period t;

S_i represents the startup cost of unit i;

$u_{i,t}$ represents the operating status of unit i in time period t, which is a binary variable to be optimized;

$y_{i,t}$ represents the startup status of unit i in time period t, which is a binary variable to be optimized;

At the same time, this paper handles carbon emission costs by treating the carbon price as an exogenous variable, calculated as follows:

$$C' = P_{i,b,t} E_i \omega \tag{2}$$

Where,

$E_i$represents the carbon emission intensity coefficient corresponding to unit i;

ω represents the price of the carbon emission allowance in the carbon emission trading market; Thus, the carbon emission cost for a coal-fired power unit is calculated, and this cost is eventually incorporated into the segmented pricing for thermal power units as part of the variable costs.

The establishment of the above model also takes into account various constraints. The constraint conditions are as follows:

Total output constraint for the generating units,

$$P_{i,t} = \sum\nolimits_{b=1}^{B} P_{i,b,t} \tag{3}$$

Grid-wide power balance constraint,

$$\sum\nolimits_{i=1}^{I} P_{i,t} = D_t \tag{4}$$

Unit power segment constraint,

$$0 \le P_{i,b,t} \le u_{i,t} P_{max,i,b,t} \tag{5}$$

Unit minimum output constraint,

$$P_{i,t} \ge u_{i,t} P_{min,i,t} \tag{6}$$

Where,

$P_{i,t}$ represents the output of unit i in time period t, which is the variable to be optimized;

$P_{min,i,t}$ represents the minimum output of unit i in time period t;

D_t represents the load in time period t;

$P_{max,i,b,t}$ represents the power upper limit of unit i in segment b and time period t;

Unit ramping constraint,

$$\begin{cases} P_{i,t} - P_{i,t-1} \le P_{U,t} \\ P_{i,t-1} - P_{i,t} \le P_{D,t} \end{cases} \forall t > 1 \tag{7}$$

$$\begin{cases} P_{i,1} - P_{i,0} \le P_{U,t} \\ P_{i,0} - P_{i,1} \le P_{D,t} \end{cases} \tag{8}$$

Thermal reserve constraint,

$$\sum\nolimits_{i=1}^{I} (u_{i,t} P_{max,i,t} - P_{i,t}) \ge R_t \tag{9}$$

Where,

$P_{U,t}$ and $P_{D,t}$ respectively represent the up and down ramp rates for unit i in time period t;

$P_{i,0}$ represents the initial output of unit i;

$P_{max,i,t}$ represents the maximum output of unit i in time period t;

R_t represents the system's thermal reserve requirement;

Constraints on the upper and lower limits of the output for new energy sources such as wind power,

$$P_{i,t}^{\prime min} \leq P_{i,t}^{\prime} + \Delta P_{i,t}^{\prime} \leq P_{i,t}^{\prime max} \tag{10}$$

In the equation: $P_{i,t}^{'}$, $P_{i,t}^{'min}$ and $P_{i,t}^{'max}$ respectively represent the active power injection, minimum output power, and maximum output power of wind power at node i.

Constraints on the short-term variation range of the output for new energy sources such as wind power, based on statistical data, estimates for the range of changes in the output of new energy sources, whether it increases or decreases, within a unit of time can be obtained,

$$a_{i,t}^{\prime min} \leq \Delta P_{i,t}^{\prime} \leq a_{i,t}^{\prime max} \tag{11}$$

In the equation: $a_{i,t}^{'max}$ and $a_{i,t}^{'min}$ respectively represent the upper and lower limits of the possible changes in wind power output at node i.

Unit state constraint,

$$u_{i,t} - u_{i,t-1} = y_{i,t} - z_{i,t} \ \forall t > 1 \tag{12}$$

$$u_{i,1} - u_{i,0} = y_{i,1} - z_{i,1} \tag{13}$$

Minimum operating time constraint,

$$\sum\nolimits_{\tau=t-T_{on,i}+1}^{t} y_{i,\tau} \leq u_{i,t} \tag{14}$$

Minimum shutdown time constraint,

$$\sum\nolimits_{\tau=t-T_{off,i}+1}^{t} z_{i,\tau} \leq 1 - u_{i,t} \tag{15}$$

Where,

$z_{i,t}$ represents the shutdown status variable for unit i in time period t, which is a binary variable to be optimized;

$u_{i,0}$ represents the initial operating status of unit i;

$T_{on,i}$ represents the minimum operating time for unit i;

$T_{off,i}$ represents the minimum shutdown time for unit i;

Transmission line flow constraint,

$$0 \leq f \leq \bar{f} \tag{16}$$

In the equation, f and $\bar{f}$ represent the active power flow and its upper limit for the network branch. The elements f_{ij} in the vector f have the following specific expression, where f_{ij} represents the active power transmitted between node i and node j.

$$f_{ij} = V_i V_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \tag{17}$$

In the given model, the states and outputs of each unit for each time period serve as the decision variables. To account for the influence of wind power volatility on the total system cost and carbon emission cost, various levels of volatility are incorporated. More precisely, random volatility values are generated within a specified range to modify the magnitude of new energy output.

3.Example analysis

3.1.Model solving

Because the issue discussed in this paper is a typical mixed-integer programming problem, and taking into account the capabilities of the Gurobi solver in Matlab, which can effectively handle large-scale linear and mixed-integer linear problems while supporting multi-objective optimization, the primary choice for solving the low-carbon dispatch model of the power system, considering wind power output volatility, is the Gurobi solver in Matlab.

3.2.Example parameters

To validate the feasibility of the low-carbon dispatch model for the power system considering the fluctuation of wind power output proposed in this paper, we use data from a specific region in the northwest area as a case study to validate the aforementioned model. In the case study system, there are a total of 208 thermal power units, all of which are coal-fired units, with a minimum operating time and minimum downtime both set at 8 hours. Additionally, there are 5 wind power units, and their output over a month (30 days) is illustrated in the following figure 1.

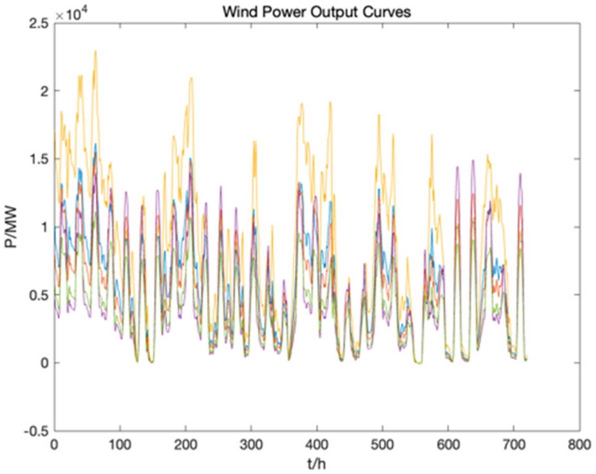

Figure 1. Wind Power Output Curve Graph.

For the load side, this paper uses the load data from five major regions in the northwest area over one month as parameter samples, as shown in the figure below. Ultimately, under these conditions, the model described in this paper is used for continuous rolling optimization over 30 days, allowing for the analysis of the impact of varying wind power volatility on the overall system cost and carbon emission cost, as shown in Figure 2.

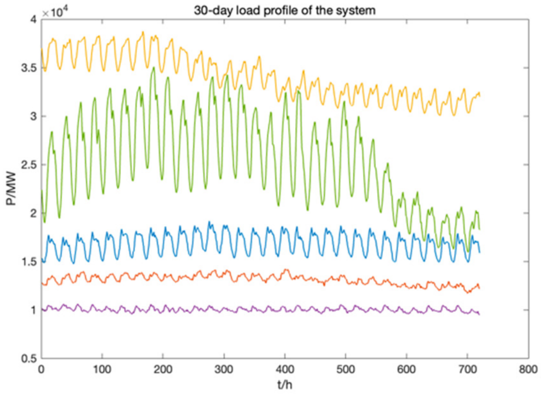

Figure 2. Load profile for the system over 30 days.

3.3.Results and Analysis

To investigate the impact of wind power volatility on the overall system cost and carbon emission cost, this study constructs several scenarios with different levels of volatility and analyzes the operational outcomes in each scenario, as shown in Figure 3.

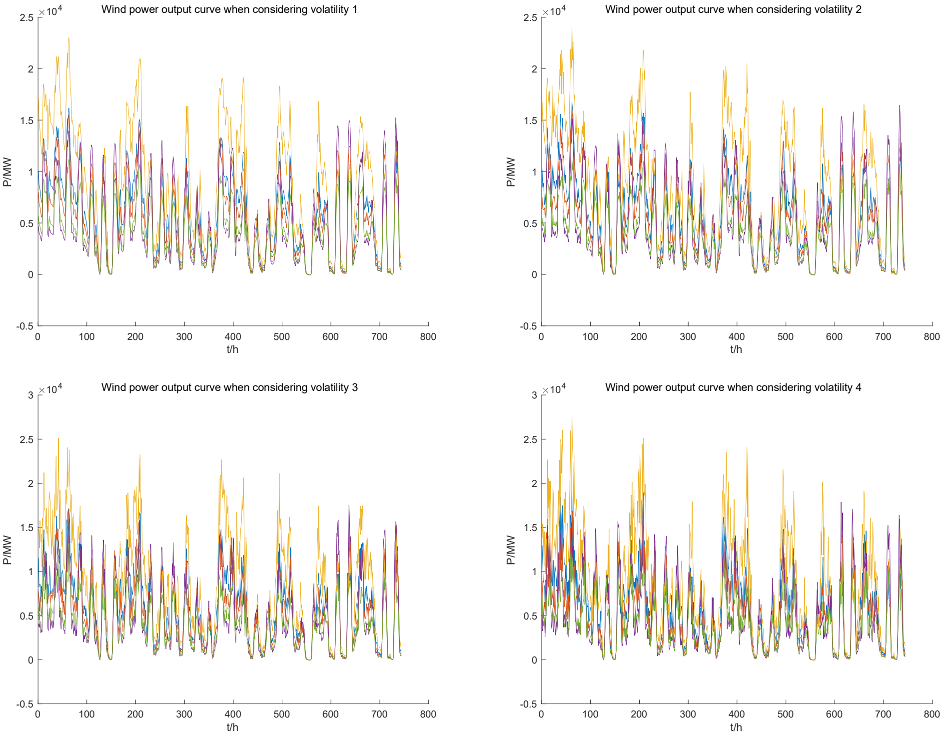

Figure 3. Wind power output curves considering wind power volatility.

Scene 1: Wind power volatility is 0;

Scene 2: Wind power volatility is 10%;

Scene 3: Wind power volatility is 20%;

Scene 4: Wind power volatility is 30%;.

After calculations, it is found that when the volatility value is set to 0, the average cost for one day, under the condition of satisfying the safety constraint for unit combinations, is approximately 552,298,286.91 yuan. The average cost for thirty days is around 16,568,948,607.35 yuan. When the volatility value is set to 10%, with a carbon price (cp) of 10, under the condition of satisfying the safety constraint for unit combinations, the average cost for one day is approximately 552,459,149.99 yuan. The average cost for thirty days is around 16,573,774,499.63 yuan. At this point, only one unit out of all 208 units experienced changes in startup and shutdown status. This unit is the 49th unit, and its startup and shutdown status changed 30 times over the course of 30 days. When the volatility value is set to 20%, with a carbon price (cp) of 10, under the condition of satisfying the safety constraint for unit combinations, the average cost for one day is approximately 552,848,403.32 yuan. The average cost for thirty days is around 16,585,452,099.51 yuan. At this point, out of all 208 units, 4 units experienced changes in startup and shutdown status. These units are the 49th unit, which changed 30 times in 30 days; the 89th unit, which changed 29 times in 30 days; the 113th unit, which changed once in 30 days; and the 158th unit, which changed 29 times in 30 days. When the volatility value is set to 30%, with a carbon price (cp) of 10, under the condition of satisfying the safety constraint for unit combinations, the average cost for one day is approximately 554,831,463.68 yuan. The average cost for thirty days is around 16,644,943,910.54 yuan. At this point, out of all 208 units, 5 units experienced changes in startup and shutdown status. These units are the 5th unit, which changed once in 30 days; the 49th unit, which changed 19 times in 30 days; the 158th unit, which changed 18 times in 30 days; the 159th unit, which changed 18 times in 30 days; and the 172nd unit, which changed once in 30 days.

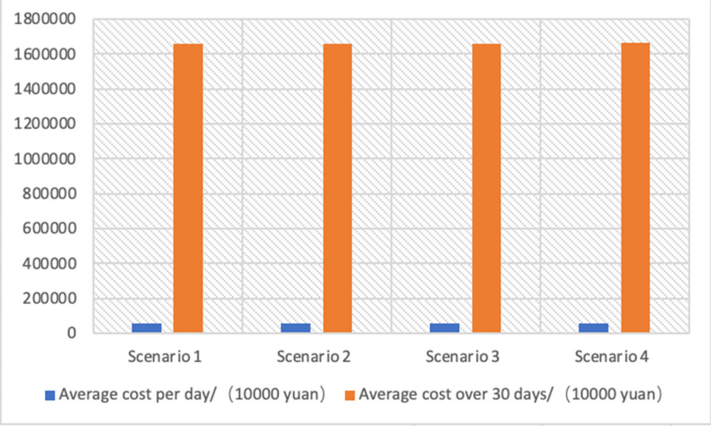

Figure 4. Total system cost.

As shown in figure 4, as the volatility increases, the startup and shutdown status of some units will change within 30 days, leading to increased startup and shutdown costs for these units. Additionally, carbon emission costs may also increase, resulting in an overall cost increase. Therefore, to reduce the total cost, measures should be taken to decrease the volatility value.

4.Conclusion

Due to the volatility and uncertainty of new energy sources such as wind power, this paper establishes a low-carbon dispatch model for power systems considering wind power output volatility. The study analyzes its impact on the overall system cost and carbon emission cost, providing theoretical and decision support for improving the economic efficiency of power system operation. The case study shows that with the continuous increase in wind power volatility, there are changes in the startup and shutdown status of conventional power generation units. This not only affects the safe and stable operation of the power system but also leads to an increase in startup and shutdown costs, along with an increase in carbon emission costs. Ultimately, this results in an overall increase in system costs, affecting the economic efficiency of system operation.

Therefore, in future research, to reduce overall costs and enhance the economic efficiency of system operation, measures should be taken to decrease the numerical value of its volatility.

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