A wind - light - fire co-generation strategy considering dual carbon targets and emission costs

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Abstract. New energy generation is the main way to replace fossil energy generation and solve the current environment and energy problems, considering that thermal power still accounts for a large proportion of the energy mix and the government’s “carbon peak” and “carbon neutral” targets. In this paper, a scheduling model of wind-light-fire combined power generation is built, considering the environmental costs such as desulfurization, denitration and carbon treatment costs. This model could ensure power grid safe operation, reduce emissions of SO2, NOx and CO2, and increase wind power and photovoltaic power generation accommodation. It took the minimum system operation cost as objective, based on traditional economic dispatching of wind power and photovoltaic, considering thermal unit cost, sewage and carbon treatment costs, operation cost of wind power and photovoltaic power generation, etc. The model was solved with an improved genetic algorithm. Taking IEEE 30-node 6-machine system as an example, proving validity and rationality of the model.

1.Introduction

With the increasing attention of the country to environmental protection, in the future energy development strategy, on the one hand, it will vigorously develop the renewable energy represented by wind power and solar power; on the other hand, more stringent emission standards will be put forward for nitrogen and sulfur pollutants and CO2 emissions from coal-fired power plants. This paper takes into account the cost of desulfurization, denitration, carbon emission and so on in the dispatching of wind-light-fire joint power generation, which is of great significance to improve the economy and environmental protection of power grid operation.

In the existing literature, SO2, NOx and CO2 are rarely included in the environmental cost, and the literature does not pay attention to the potential carbon emissions of wind power and photovoltaic power generation. At present, the goals of "carbon peak" and "carbon neutral" have been put on the agenda, and the installed capacity and power generation of new energy continue to increase significantly. Considering the carbon emission target and environmental cost, the research on the scheduling of wind - light - fire joint power generation is of great significance for the rapid development of new energy in the future and the early realization of the goal of "carbon peak" and "carbon neutral". Considering desulfurization and denitration is presented in this paper, carbon emissions and other environmental costs and the total cost of the economic wind-light-fire joint power generation scheduling model, the desulfurization and denitration device operating cost of wind power, photovoltaic and the cost of carbon emissions is introduced into the model, to consider the grid safe
and economic operation of reducing emissions of pollutants and greenhouse gases at the same time. With the goal of minimizing the total cost of the system, this paper explores the balance between wind farm and photovoltaic power station and thermal power unit operating cost and environmental cost, and determines the optimal access capacity of wind power and photovoltaic power generation.

2. Wind-Light-Fire Economic Scheduling Model with Environmental Protection Considered
The objective function is to minimize the economic cost of the system. The economic objective function consists of five parts: sewage discharge and carbon treatment cost (CO₂ treatment cost, operation cost of desulfurization and denitrification device), operation cost of wind power, operation cost of photovoltaic power generation, operation cost of thermal power and network loss cost.

2.1. Thermal power operating costs
The grid connection of wind power and photovoltaic power generation will affect the output of thermal power units and even the frequent start-up and shutdown of thermal power units. The operating costs of thermal power units include fuel costs, start-up costs of thermal power units and rotating standby costs. Fuel cost and unit start-stop cost are expressed as

\[ f_i = \sum_{t=1}^{T} \sum_{i=1}^{N} \left[ \left( a_i P_i^2 + b_i P_i + c_i \right) + S_{it} u_{it} \left( 1 - u_{i(t-1)} \right) \right] \]  

(1)

In this formula, \( f_i \) represents the fuel cost and start-up cost of thermal power unit; \( P_i \) is the generating power of unit \( i \) in time period \( t \); \( a_i \), \( b_i \) and \( c_i \) respectively represent the fuel cost coefficient of unit \( i \); \( u_{it} \) represents the operating state of unit \( i \) at time \( t \), \( u_{it} = 0 \) denotes stop state, \( u_{it} = 1 \) represents running state; \( S_{it} \) represents the start-up cost of unit \( i \) at time \( t \).

Since the uncertainty of wind power and photovoltaic power generation causes the increase of rotating reserve capacity, the rotating reserve cost is expressed as

\[ f_2 = \sum_{t=1}^{T} \sum_{i=1}^{N} \left( \alpha_t U_{it} + \beta_t D_{it} + \gamma_t R_{it} \right) \]  

(2)

In the formula, \( f_2 \) represents the cost of reserve capacity; \( U_{it}, D_{it} \) and \( R_{it} \) respectively represent the positive rotation reserve capacity, negative rotation reserve capacity and accident rotation reserve capacity of unit \( i \) at time \( t \); \( \alpha_t \), \( \beta_t \) and \( \gamma_t \) represent the positive, negative cost coefficients of rotation reserve and accident reserve of unit \( i \) respectively.

2.2. Wind power operation cost
In this paper, the operation cost of wind power only considers the operation and maintenance cost, and is approximately expressed as a linear relationship with the power of wind power generation.

\[ f_3 = \sum_{t=1}^{T} C_W P_{wt} \]  

(3)

\( f_3 \) is the operation cost of wind power; \( C_W \) is the cost coefficient of wind power operation and maintenance; \( P_{wt} \) is the output power of the wind farm at time \( t \).

2.3. Operation cost of photovoltaic power generation
In the case of photovoltaic power generation, investment cost, depreciation cost and other expenses of photovoltaic power generation are ignored, and only its operation and maintenance cost is considered, which is approximately expressed as a linear relationship with the power of photovoltaic power generation.
In this equation, $f_4$ is the operating cost of photovoltaic power generation; $C_p$ is the correlation coefficient of operation and maintenance; $P_{pt}$ is the output power of the photovoltaic power station at time $t$.

### 2.4. Sewage and carbon treatment costs

In this paper, the emissions of pollutants SO$_2$ and NO$_x$, greenhouse gases CO$_2$ from thermal power plants and the potential emissions CO$_2$ from wind power and photovoltaic power generation are considered.

The cost of sewage discharge and carbon treatment is divided into three categories. The first category is the cost of desulfurization, denitrification and carbon treatment of thermal power plant $f_5$. The second category is the potential CO$_2$ treatment cost $f_6$; The third category is the potential CO$_2$ treatment cost $f_7$ generated by photovoltaic power generation.

\begin{align*}
  f_5 &= (T_0 + T_1) \sum_{t=1}^{T} \sum_{i=1}^{N} P_{it} + \sum_{t=1}^{T} \sum_{i=1}^{N} \alpha k_{hi} P_{it} \\
  f_6 &= \sum_{t=1}^{T} \alpha k_{ri} P_{wt} \\
  f_7 &= \sum_{t=1}^{T} \alpha k_{rt} P_{pt}
\end{align*}

In the formula, $P_{it}$ is the generating power of thermal power unit $i$ in time period $t$, and the unit is MW. $k_{hi}$ and $k_{ri}$ are the emission intensity of CO$_2$ for both the thermal power units and the renewable energy sources respectively in kg/MW∙h; $P_{wt}$ and $P_{pt}$ are respectively the generating power of wind turbine and photovoltaic power station in time period $t$; $\alpha$ is the comprehensive coefficient of CO$_2$ environmental damage, unit is yuan/kg.

The total operating cost of a thermal power unit is composed of fuel cost, start-up and shutdown cost of the unit, rotation and standby cost, desulfurization and denitration cost, and carbon treatment cost. Therefore, the total operating cost of a thermal power unit $F_1$ is:

\begin{equation}
  F_1 = f_1 + f_2 + f_3
\end{equation}

The total operating cost of wind turbine is composed of operation and maintenance cost and carbon treatment cost, so the total operating cost of wind turbine $F_2$ is:

\begin{equation}
  F_2 = f_5 + f_6
\end{equation}

Similarly, the total operating cost of photovoltaic power generation $F_3$ is:

\begin{equation}
  F_3 = f_4 + f_7
\end{equation}

In summary, the objective function of the wind-light-fire economic scheduling model with environmental protection is:

\begin{equation}
  \min F = \varphi_1 F_1 + \varphi_2 F_2 + \varphi_3 F_3
\end{equation}

$F$ is the total economic cost of the system; $\varphi_1$, $\varphi_2$ and $\varphi_3$ are weight coefficients.
3. Constraint conditions of system safe operation

3.1. Power balance constraint

$$\sum_{i=1}^{T} \sum_{t=1}^{N} P_{it} + \sum_{t=1}^{T} P_{wt} + \sum_{t=1}^{T} P_{pt} - \sum_{t=1}^{T} P_{it} = 0$$  \hspace{1cm} (12)

3.2. Thermal power unit output constraints

$$P_{it_{\min}} \leq P_{it} \leq P_{it_{\max}}$$  \hspace{1cm} (13)

3.3. Wind power output constraint

$$0 < P_{wt} \leq P_{wt_{\max}}$$  \hspace{1cm} (14)

3.4. Output constraint of photovoltaic power station

$$0 < P_{pt} \leq P_{pt_{\max}}$$  \hspace{1cm} (15)

4. Model Solving

The above economic dispatching model is a complex multi-dimensional nonlinear programming model. Considering the scale of the actual power system, the traditional mathematical optimization algorithm is not suitable to solve the model. Considering that the genetic algorithm in the heuristic algorithm does not need the initial feasible solution, it is more suitable for solving such models with a large number of nodes, so this paper adopts the genetic algorithm to solve the above models, and further improves the genetic algorithm. On the basis of the standard genetic algorithm, the elite reservation strategy is introduced. The elite reservation strategy can effectively avoid the optimal individuals from being destroyed by hybridization, and the standard genetic algorithm with the elite reservation strategy is globally convergent.

5. The example analysis

5.1. An overview of the example system

In order to verify the effectiveness of the model, this paper adopts the IEEE-30 node system for simulation analysis, as shown in Figure 1.

![Figure 1: Structure diagram of IEEE 30-bus system](image)
Assume that the nodes 1, 2, 5, 8, 11 and 13 are all thermal power units, and the parameters of the 6 thermal power units are shown in Table 1. The selected node 26 is the grid-connected node of photovoltaic power station and node 16 is the grid-connected node of wind farm. Firstly, the change of total economic cost under different scale of renewable power is analyzed. Then the economic dispatching model established in this paper is compared with the traditional dispatching model without considering the operation cost of desulfurization and denitration plant and carbon treatment cost.

Each scheduling day is set to be 24 time periods, and each time period is 1 hour. Wind power, photovoltaic power generation and load forecast power are shown in Figure 2. In the optimization process, the weight coefficients of the economic objective function \( \phi_1 = 0.6, \phi_2 = 0.2, \phi_3 = 0.2 \), the wind power operation and maintenance cost coefficient \( C_w \) is 500 yuan/MW, the photovoltaic operation and maintenance correlation coefficient \( C_p \) is 600 yuan/MW, and the desulfurization cost per unit power supply \( T_0 \) is 19.8 yuan/(MW·h). The denitrification cost \( T_1 \) per unit electricity supply is 11.2 yuan/(MW·h). According to literature, desulfurization operation cost, denitration operation cost, carbon emission intensity and carbon treatment cost of wind, light and fire power supply are shown in Table 2.

### Table 1 Parameters of thermal power units

| Unit | Output ceiling \( P_{\text{max}}/\text{MW} \) | The lower limit of output \( P_{\text{min}}/\text{MW} \) | Unit climbing rate \( r_u/(\text{MW/h}) \) | Fuel cost factor \( a_i/\text{(yuan/MW}^2) \) | \( b_i/\text{(yuan/MW)} \) | \( c_i/\text{yuan} \) |
|------|-----------------------------------|----------------|----------------|----------------|----------------|----------------|
| 1    | 200                               | 50             | 100            | 0.0014         | 200            | 75             |
| 2    | 130                               | 20             | 40             | 0.0021         | 175            | 700            |
| 3    | 80                                | 20             | 35             | 0.0031         | 165            | 350            |
| 4    | 50                                | 15             | 25             | 0.0023         | 100            | 1200           |
| 5    | 30                                | 10             | 15             | 0.0009         | 150            | 500            |
| 6    | 40                                | 12             | 20             | 0.0008         | 200            | 500            |

### Table 2 Parameters of power station

| Power source type | Desulfurization operation cost(yuan/ MW·h) | Denitration operation cost(yuan/ MW·h) | Carbon emission intensity (kg/ MW·h) | Cost of carbon treatment (yuan/kg) |
|-------------------|-------------------------------------------|----------------------------------------|-------------------------------------|----------------------------------|
| Thermal power     | 19.8                                      | 11.2                                   | 890                                 | 0.1445                           |
| Wind power        | -                                         | -                                      | 290                                 | 0.1445                           |
| Photovoltaic power| -                                         | -                                      | 286.8                               | 0.1445                           |
5.2. Example results and analysis

5.2.1. Influence of different scale of wind power and photovoltaic power generation on dispatching results. Different access capacity of wind power and photovoltaic power generation will affect the total economic cost of the system. Therefore, the total economic cost under different scale of wind power and photovoltaic power generation is analyzed. As can be seen from the optimization results in Figure 3, at the beginning, with the access of wind power photovoltaic power generation, the total economic cost begins to decline, which indicates that the access of wind power photovoltaic power generation will reduce the fuel cost of thermal power units, the cost of carbon treatment and the operating cost of desulfurization and denitrification devices, thus reducing the total cost of the system. With the increasing capacity of wind power and photovoltaic power generation, the economic cost is rising. On the one hand, the increase of the grid-connected capacity of wind power and photovoltaic power generation leads to the increase of potential carbon dioxide emissions faster than the reduction of carbon emissions of thermal power units. On the other hand, large-scale wind power photovoltaic access will increase the volatility and uncertainty of power generation, which will gradually increase the reserved reserve capacity of conventional units. The operation cost of wind power photovoltaic itself is also rising, making the total economic cost start to increase.

Figure 2 Forecasting power of wind power, photovoltaic power and load

Figure 3 Total economic cost curve under different wind power and Photovoltaic scales
5.2.2. Comparison of different scheduling models. Introducing environmental cost in order to reflect the economic objective function and the combination of wind power, photovoltaic running cost impact on economic and environmental benefits, through this article scheduling model and the traditional desulfurization denitration device running cost for carbon and comparison of the dispatching model for the processing cost, the calculation results of different scheduling model as shown in Figure 4, Figure 5.

![Figure 4](image-url)  Wind power online capacity curves of different Scheduling models

![Figure 5](image-url)  Photovoltaic capacity curves of different Scheduling models

By comparing the two models, the optimal grid-connection capacity of stroke power generation and photovoltaic power generation in Model 1 is 165MW and 121MW respectively, and the optimal access capacity of stroke power generation and photovoltaic power generation in Model 2 is 120MW and 100MW respectively. Although the total economic cost increases by 6.3%, the access capacity of wind power and photovoltaic power generation also increases. It maximizes the use of renewable energy, in line with the concept of sustainable development in China.

As can be seen from the optimization results in Table 3, after considering the environmental cost, although the total optimal economic cost increases by 127,700 yuan, the online capacity of wind power and photovoltaic power generation increases by 45MW and 21MW respectively, and the SO\textsubscript{2} emissions and the NO\textsubscript{x} emissions are reduced by 16.5% and 14% respectively. The emission of CO\textsubscript{2} was reduced by 12.25%.
Table 3  Comparison of optimization results of the two models

| Model   | Total economic cost/ten thousand yuan | Wind power access capacity /MW | Photovoltaic access capacity /MW | $CO_2$ emissions /t | $SO_2$ emissions /t | $NO_x$ emissions /t |
|---------|--------------------------------------|-------------------------------|---------------------------------|----------------------|---------------------|---------------------|
| Model 1 | 216.56                               | 165                           | 121                             | 4886.93              | 2.63                | 2.74                |
| Model 2 | 203.79                               | 120                           | 100                             | 5569.28              | 3.15                | 3.19                |

The model can comprehensively consider economic benefits and environmental benefits of energy conservation and emission reduction, which verifies the effectiveness and reliability of the scheduling model.

6. Conclusion
In this paper, based on the "double carbon target" and the environmental pollution problem, the environmental cost of desulfurization, denitration and carbon treatment as well as the wind-light-fire joint power generation scheduling model are constructed to rationally plan the capacity of wind power and photovoltaic power grid and reduce the emission of pollutants and CO$_2$. The combined output of wind power generation, photovoltaic power generation with low carbon treatment cost and thermal power generation with high carbon treatment cost can not only reduce the emission of CO$_2$, but also reduce the emission of pollutants SO$_2$ and NO$_x$.

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