Optimized dispatching based on wind-photovoltaic-hydropower-thermal-bundled strategy

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Abstract. The rapid development of wind power and photovoltaic is conducive to optimizing the energy structure and resolving fossil energy crisis, in response to the strategic direction of energy saving and emission reduction in China. However, the intermittence and fluctuation of wind, photovoltaic and other renewable energy sources pose greater challenges to the secure and stable operation of the power grid. Therefore, it is of theoretical significance and practical value to study the optimal dispatching of power system with wind and photovoltaic large-scale connected to grid. This work proposes an optimal scheduling strategy based on wind-photovoltaic-hydropower-thermal bundled according to the energy resources reasonable allocation proportion. The strategy gives full play to the complementary characteristics of energy, and realizes the comprehensive optimization of system peak shaving, economic cost and environmental benefit. The bundled power configuration layer defines the bundled fitness index, which takes into account the comprehensive influences of conventional unit utilization rate, load tracking degree and wind power abandonment. Based on the commercial optimization software CPLEX, the output of conventional hydropower units and the combination of thermal power units are solved. Finally, the feasibility of the model is verified by a case study.

1. Introduction

With the continuous depletion of fossil energy, renewable energy generation such as wind power and photovoltaic has developed rapidly, and the permeability in power system has also been increasing. However, the uncertainty caused by the random fluctuation of wind and photovoltaic resources has brought great impact to the safe and stable operation of power system. Therefore, it is urgent to purpose a reasonable optimized dispatching strategy at the operational level to meet the demand of a future power grid with high proportion of renewable energy [1-2].

The existing research mainly proposes to solve the above problems from three aspects. 1) Improve the accuracy of wind and photovoltaic output forecasting, that is, to reduce the error of wind and photovoltaic output forecasting. In view of the impact of uncertainty on system scheduling, a mathematical model reflecting the fluctuation of new energy output is established [3-4]; 2) Use the technical characteristics of energy storage to improve the grid-connection characteristics of wind and photovoltaic renewable energy and ensure the stable operation environment of the power system. However, the promotion of large-scale energy storage has not reached the stage of engineering practice, and the investment cost is high [5]; 3) Make full use of the complementary characteristics of...
energy, reasonably configure the bundled proportion of conventional power (hydropower, thermal), wind power and photovoltaic, and realize the efficient consumption of new energy on the premise of ensuring reliable power supply of the system [6-7]. Based on the energy management strategy and the principle of optimal configuration, the Reference [8] constructed a capacity optimal configuration model for the wind-wind-optical-battery complementary power generation system. Under the guidance of ensuring the minimum total cost of the system, it made full use of the complementary characteristics between wind power and photovoltaic to make the wind-solar output fluctuation of grid connection meet the online requirements. Reference [9] comprehensively considered the energy type and power type constraints of the battery, as well as the three goals of cost, LPSP and SPSP. Under the premise of satisfying the reliability of load power supply, it reasonably configured the wind-photovoltaic storage capacity and quickly obtained the optimal wind-view storage combination. Reference [10] established the power output configuration model of wind-thermal bundled delivery system, and evaluated the operation effect of the system under different wind-thermal configuration proportions. Most of the above References focus on the optimal capacity planning and configuration of hybrid systems and the coordination and control of various power sources. In addition, the hybrid system that has been studied usually contains two or three kind of power sources only, and rarely involves the hybrid system that contains four or more kinds of power sources.

Therefore, aiming at the wind-photovoltaic-hydropower-thermal hybrid power generation system and giving full play to the complementary characteristics among energy sources, this work proposes an optimal scheduling based on bundled wind-photovoltaic-hydropower-thermal strategy according to a reasonable allocation proportion, so as to realize the integrated optimization of peak shaving, economic cost and environmental benefits of the system. The bundled power supply configuration layer defines the bundled fitness index, which takes into account the comprehensive influence of conventional unit utilization rate, load tracking degree and wind abandoning to achieve the purpose of peak cutting and valley filling and smooth load curve. Then on the revised load curve, the unit output is arranged based on the peak shaving capacity of conventional hydropower units to achieve the purpose of secondary peak shaving. Finally, the residual load is distributed to the thermal power unit based on the principle of minimum economic cost to complete the power scheduling of the multi-energy hybrid system. At last, the feasibility of the model is verified by a case study.

2. Configuration strategy of bundled power supply

The bundled fitness index was defined to determine the optimal configuration ratio, and the comprehensive influence of bundled power output on the tracking capacity of load, the utilization rate of conventional units and the amount of wind and photovoltaic abandoned were also considered. Under the optimal bundled ratio between new energy and conventional energy, the power structure is relatively reasonable, and the modified load curve is stable after the power output is reduced by the load curve. At the same time, the utilization rate of the bundled hydropower units and thermal power is high, and the amount of wind and photovoltaic abandoning is small.

In this work, a total of six combination modes of bundled power supply are proposed, including wind-hydropower, wind-thermal, photovoltaic-hydropower, photovoltaic-thermal, wind-photovoltaic-hydropower and wind-photovoltaic-thermal. According to the bundled fitness index, the optimal configuration proportion is obtained in each mode, so that the bundled fitness is the highest and the comprehensive benefit of the power system is the best.

The load tracking coefficient is defined to evaluate the smoothness of load curve after the bundled power supply access. The closer the load tracking coefficient is to 1, the stronger the ability of tying power supply output to track load fluctuation is, the smoother the load curve is, and the remaining load timing characteristics that need to be borne by conventional units are more stable.
\[ \mu_i = \frac{\sum_{t=1}^{T} (P_{G,t,i} - P_{G,i,av})(P_{D,t} - P_{D,av})}{\sqrt{\sum_{t=1}^{T} (P_{D,t} - P_{D,av})^2} \sqrt{\sum_{t=1}^{T} (P_{G,t,i} - P_{G,i,av})^2}} \] (1)

where \( \mu_i \) represents the load tracking coefficient of bundled power supply, \( i = 1,2 \), corresponding to the above two bundled modes respectively, namely, wind-photovoltaic-hydropower station and wind-photovoltaic-thermal power station; \( P_{G,t,i} \) represents the total output of power supply \( i \) in time \( t \), and \( P_{G,i,av} \) represents the average output value of power supply \( i \) in time period 24; \( P_{D,t} \) is the load at time \( t \), \( P_{D,av} \) is the average load value in 24 time periods, and \( T \) represents the number of time periods in the scheduling cycle.

By adjusting the configuration ratio to adjust the output of bundled power supply, the output change trend of bundled power supply is as close as possible to the load change \( P_{D,t} \).

The utilization rate of conventional units is defined to quantitatively reflect the effect of bundled ratio on the operation efficiency of conventional units.

\[ \eta = \frac{\int_{1}^{24} P_{G,t}dt}{24 \times P_{G,\text{max}}} \] (2)

where \( \eta \) represents the utilization rate of conventional units, \( P_{G,t} \) represents the output of bundled power supply at each moment \( t \), \( P_{G,\text{max}} \) represents the maximum output of bundled power supply.

The higher the allocation proportion of bundled power is, the lower the utilization rate of conventional energy bundled with new energy. Therefore, the determination of a reasonable bundled proportion should take into account the utilization efficiency of conventional units and the load tracking coefficient at the same time to achieve the comprehensive optimal.

Define the proportion coefficient of wind and photovoltaic abandonment, and characterize the proportion of wind and photovoltaic abandoning to total wind and photovoltaic power generation.

\[ \lambda = \sum_{j=1}^{2} \frac{P_{aba,w,j} + P_{aba,sv,j}}{P_{w,j} + P_{s,j}} \] (3)

where \( \lambda \) represents the proportion coefficient of wind abandonment, \( P_{aba,w,j} \) and \( P_{aba,sv,j} \) represents the abandoning amount of wind power and photovoltaic at time \( t \), \( P_{w,j} \) and \( P_{s,j} \) shows the total output of wind power and photovoltaic generation at time \( t \).

In order to comprehensively consider the role of the three indicators mentioned above, the fitness index of bundled was defined to determine the optimal allocation ratio. This index was combined with the three indicators mentioned above to give different weight coefficients of corresponding indicators. The calculation method of weight coefficients was referred to in the Reference [11].

\[ \rho = \gamma_1 \mu + \gamma_2 \eta + \gamma_3 \lambda \] (4)

where \( \gamma_1, \gamma_2, \gamma_3 \) represents the corresponding weight coefficient.

The conventional hydropower that does not run in bundles with wind power and photovoltaic is arranged to undertake the task of peak load regulation for the second time, so that the load fluctuation left for the conventional thermal power units is small, and the coal consumption of thermal power units will be reduced when they start and stop, thus greatly improving their operating environment.

Calculate the standard deviation of the residual load curve after eliminating the output of unbundled hydropower units to describe their peak shaving capacity:

\[ \sigma = \sqrt{\frac{1}{T-1} \sum_{j=1}^{T} (P_{fix,j} - P_{fix,av})} \] (5)
where \( P_{fix,t} \) represents the remaining load after arranging the unbundled hydropower unit, and \( P_{fix,av} \) represents the average value of the remaining load.

Conventional thermal power units are arranged to bear the residual load. Reasonable combination of units and output plan can reduce the coal consumption and the numbers of starts and stops. It can not only improve the reliability of operation, but also reduce the emission of polluting gas and reduce the cost of environmental governance.

\[
\omega = \frac{\sum_{t=1}^{T} \sum_{j=1}^{N_t} [u_{j,t} \ast f_j(P_{T,j,t})] + u_{j,t}(1-u_{j,t})C_{T,j}^d}{E_{all}}
\]

where \( \omega \) represents unit coal consumption; \( u_{j,t} \) represents the on/off variable of thermal power unit, running at 1 and stopping at 0; \( f_j \) is the coal consumption characteristic function of the unit, and is taken as a quadratic function; \( P_{T,j,t} \) represents the output of thermal power unit \( j \) at time \( t \); \( C_{T,j}^d \) represents the start-up coal consumption of thermal power unit \( j \) at time \( t \); \( N_T \) represents the number of conventional thermal power. \( E_{all} \) represents the total power generation of thermal power units in the \( T \) dispatching cycle.

3. Optimized dispatching model based on bundled wind-photovoltaic-hydropower-thermal strategy

3.1. Objective function

The optimal scheduling model based on wind-hydropower thermal bundled strategy needs to maximize the peak shaving benefit, economic benefit and environmental protection benefit of the system by giving full play to the regulating ability of the bundled power supply and satisfying the operating constraints of the system. In this work, the scheduling model is divided into three layers, respectively from the bundled power supply configuration layer, the conventional hydropower unit dispatching layer and the conventional thermal power unit dispatching layer to complete the optimization scheduling tasks based on different objective functions.

\[
\begin{align*}
\max \quad & F_1 = \rho \\
\min \quad & F_2 = \sigma \\
\min \quad & F_3 = \omega
\end{align*}
\]

3.2. Constraint conditions

1) System power balance constraint

\[
\sum_{t=1}^{T} \sum_{j=1}^{N_t} [u_{j,t} \ast P_{G,j,t}] + \sum_{k=1}^{N_h} u_{k,t} P_{H,k,t} + \sum_{j=1}^{N_t} u_{j,t} P_{T,j,t} - P_{\text{load},t} = P_{D,t}
\]

where the value of \( u_{j,t}, u_{k,t}, u_{j,t} \) indicates whether the bundled power supply, hydropower unit and thermal power unit generate power or not, "1" means the unit is in operation, and "0" means the unit is out of operation. \( P_{H,k,t} \) represents the output of hydropower unit \( k \) at time \( t \).

2) Unit output constraint

\[
\begin{align*}
0 & \leq P_{w,m,j} \leq P_{w,m,\text{max}} \quad (m = 1,2,\ldots,N_w) \\
0 & \leq P_{s,n,j} \leq P_{s,n,\text{max}} \quad (m = 1,2,\ldots,N_s) \\
0 & \leq P_{H,k,\text{min}} \leq P_{H,k,\text{max}} \quad (m = 1,2,\ldots,N_H) \\
0 & \leq P_{T,j,\text{min}} \leq P_{T,j,\text{max}} \quad (m = 1,2,\ldots,N_T)
\end{align*}
\]
where \( P_{w,m,t}, P_{s,n,t}, P_{h,k,t}, P_{r,j,t} \) respectively represents the output of wind power \( m \), photovoltaic \( n \), hydropower \( k \) and thermal power \( j \) at time \( t \); \( N_w, N_s \) represents the number of wind power and photovoltaic units respectively; \( P_{w,m,\text{max}} \), \( P_{s,n,\text{max}} \), \( P_{h,k,\text{max}} \), \( P_{r,j,\text{max}} \) represent the maximum output of wind power \( m \), photovoltaic \( n \), hydropower \( k \) and thermal power \( j \) respectively. \( P_{w,\text{h,\min}}, P_{r,j,\text{min}} \) represent the minimum output of hydropower \( k \) and thermal power \( j \) respectively.

3) Unit climbing rate constraint

\[
\begin{align*}
\left| P_{r,j,t} - P_{r,j,t-1} \right| & \leq R_j \\
\left| P_{h,k,t} - P_{h,k,t-1} \right| & \leq R_k
\end{align*}
\]  

where \( R_j, R_k \) represents the maximum climbing speed of thermal power \( j \) and hydropower \( k \) respectively.

4) Minimum start and stop time constraint of thermal power unit

\[
\begin{align*}
& \left( T_{j,\text{min}}^m - T_{j,\text{min}}^{\text{off}} \right) (u_{j,t} - u_{j,t-1}) \geq 0 \\
& \left( T_{j,\text{min}}^{\text{on}} - T_{j,\text{min}}^m \right) (u_{j,t} - u_{j,t-1}) \geq 0
\end{align*}
\]

where \( T_{j,\text{min}}^m, T_{j,\text{min}}^{\text{off}} \) represents the minimum start and stop time of unit \( j \), \( T_{j,\text{min}}^{\text{on}} \) and \( T_{j,\text{min}}^m \) represents the continuous start and stop time of unit \( j \) to time \( t-1 \).

5) System rotational reserve constraint

The system rotation reserve constraints are divided into positive and negative rotation reserve constraints.

\[
\begin{align*}
U_{r,j,t} &= \min(R_j, P_{r,j,\text{max}} - P_{r,j,t}) \\
U_{h,k,t} &= \min(R_k, P_{h,k,\text{max}} - P_{h,k,t}) \\
D^+_r &= \sum_{j=1}^{N_r} U_{r,j,t} + \sum_{k=1}^{N_h} U_{h,k,t} \geq P_{D,r} \times a\% \\
&+ \sum_{n=1}^{N_s} P_{w,n,t} \times b\% + \sum_{n=1}^{N_s} P_{s,n,t} \times c\% \\
D^{\text{off}}_r &= \min(R_j, P_{r,j,\text{max}} - P_{r,j,t}) \\
D^{\text{on}}_h &= \min(R_k, P_{h,k,\text{max}} - P_{h,k,t}) \\
D^+_h &= \sum_{j=1}^{N_r} U_{r,j,t} + \sum_{k=1}^{N_h} U_{h,k,t} \geq P_{D,h} \times a\% \\
&+ \sum_{n=1}^{N_s} P_{w,n,t} \times b\% + \sum_{n=1}^{N_s} P_{s,n,t} \times c\%
\end{align*}
\]

where \( D^+_r, D^{\text{off}}_r \) represents the positive and negative reserve at time \( t \) respectively; \( U_{r,j,t}, D_{r,j,t} \) respectively represent the positive and negative standby of thermal power unit \( j \) at time \( t \); \( U_{h,k,t}, D_{h,k,t} \) respectively represent the positive and negative standby of the hydropower unit \( k \) at any time; \( a\%, b\%, c\% \) respectively represents the prediction errors of load, wind power and photovoltaic.

6) Wind and photovoltaic abandonment constraints

\[
\begin{align*}
0 \leq P_{\text{aba},w,n,t} & \leq \sum_{n=1}^{N_s} P_{w,n,t} \\
0 \leq P_{\text{aba},s,n,t} & \leq \sum_{n=1}^{N_s} P_{s,n,t}
\end{align*}
\]

where \( P_{\text{aba},w,n,t}, P_{\text{aba},s,n,t} \) is the amount of wind and photovoltaic abandonment at time \( t \) of the system.
4. Model solving strategy

4.1. Bundled power supply configuration layer
According to the configuration method of bundled power supply defined in chapter 1, the capacity and type of bundled power supply are determined with the objective of formula (7), and then the bundled power output is deducted from the original load curve to obtain the modified load curve:
\[ P_{\text{adj}i,t} = P_{L,t} - P_{Gi,t} \] (16)
where \( P_{\text{adj}i,t} \) is the modified load after deducting the output of baling power supply.

4.2. Hydropower unit dispatching layer
According to the revised load curve, the output of hydropower units is arranged and the optimization direction is determined with the objective of equation (8), which not only requires the capacity and climbing rate constraints of hydropower units to be satisfied, but also gives full play to the peak-shaving capacity of hydropower units to make the remaining load curve smoother.
\[ P_{fix,i,t} = P_{\text{adj}i,t} - \sum_{k=1}^{N_h} g_{i,k} P_{H,k,t} \] (17)
where \( P_{fix,i,t} \) is the residual load curve after conventional hydropower units are arranged.

4.3. Thermal power unit dispatching layer
According to the residual load curve, the unit combination and load distribution of conventional thermal power units are completed with the goal of equation (9). It should be noted that, since the coal consumption characteristics of thermal power units adopt quadratic function model, while the commercial solver CPLEX can only solve the Mixed Integer Linear Programming (MILP), the method in Reference [12] is adopted to conduct linear transformation of the model to obtain the optimal combination scheme of thermal power units.

At this point, the optimization of the model was completed, and the final scheduling scheme was obtained. The flowchart of the proposed strategy is shown in Figure 1.

![Figure 1. Flowchart of the proposed strategy.](image-url)
5. Case study

5.1. Case introduction
In this work, the measured data of a typical summer day in a certain area were selected for simulation analysis to verify the effectiveness of the proposed model. The output prediction curves of load, wind power and photovoltaic are shown in Figure 2. Considering that the demand of load, wind power and photovoltaic for rotating reserve is 5%, 13% and 10% respectively. The total installed capacity of hydropower is 4850MW and that of thermal power is 10500MW.

5.2. Case analysis

5.2.1 Bundled power supply configuration layer. Firstly, according to the predicted output curve of wind power and photovoltaic, the bundled power supply is configured. Due to adequate hydropower inflow in summer, hydropower and wind-photovoltaic bundled are given priority. The weight calculation method of reference [11] was used to solve the optimal weight, and the final fitness index of bundled was obtained.

\[ \rho = 0.582 \mu + 0.309 \eta - 0.109 \lambda \]  

(18)

According to the size of the fitness index of bundled, determine the optimal bundled proportion. The fitness index of bundled is shown in Figure 3. As the bundled proportion increases, the fitness of bundled first increases, and then decreases when it reaches the maximum value. When the bundled proportion is 1.2 (hydropower/wind-photovoltaic) and the installed capacity of bundled hydropower is 3600MW, the fitness of bundled reaches the maximum value of 0.7866.

When the bundled ratio is set as 1.2, the bundled power output curve and modified load curve after bundled output are shown in Figure 4. It can be clearly seen that when the output of bundled power is deducted from the original load demand, the modified load curve is less volatile, leaving the load borne by conventional hydropower units stable.

5.2.2 Hydropower unit dispatching layer. After the bundled power supply configuration of the first floor is completed, the load distribution of this floor is carried out with 7 hydropower units that are not bunched with wind power and photovoltaic to realize the secondary peak shaving. The output scheme of conventional hydropower is shown in Figure 5. Before the hydropower units are put into operation, the peak shaving index of the revised load curve \( \sigma \) is 189.65. When the seven remaining hydropower
units are put into operation, it is 119.32. After the output of the remaining hydropower units is arranged, the fluctuation of the remaining load is less. It can also be seen from Figure 5, that the residual load curve is smoother than the modified load curve and more suitable for thermal power units to undertake, avoiding frequent start and stop of thermal power units. It should be noted that the vertical axis only scales the upper part of the power evolution.

5.2.3. Thermal power unit dispatching layer. Finally, the working position of thermal power units is arranged according to the residual load, and the third layer optimization is completed according to the minimum unit coal consumption cost. The load curve of the model established in this work has been truncated in both the baling dispatching layer and the optimal dispatching layer of hydropower units, so the load for thermal power units remains basically unchanged. The optimization results in this work are compared with the conventional scheduling results, as shown in Table 1. The unit coal consumption of thermal power units decreased, and the system absorbed more hydropower, wind power and photovoltaic, the economic benefits and environmental benefits of the system are reflected.

6. Conclusions

In this work, an optimal scheduling strategy based on bundled wind-photovoltaic-hydropower-thermal is proposed. According to a reasonable allocation proportion, the strategy gives full play to the
complementary characteristics of energy, and realizes the comprehensive optimization of peak shaving, economic cost and environmental benefits of the system. The bundled power supply configuration layer defines the bundled fitness index, which considers the combined effects of conventional unit utilization rate, load tracking degree and wind power curtailment. In order to smooth the load curve, the conventional hydropower dispatching layer fully exerts the secondary peak-shaving effect of hydropower. The entire dispatch plan realizes the idea of multi-type power supply complementary coordinated power generation, which provides a valuable solution for the future integration of high-ratio renewable energy.

Table 1. Comparison of indicators before and after optimization.

| project                          | Before optimization | After optimization |
|----------------------------------|---------------------|--------------------|
| Unit coal consumption (kg/kWh)   | 0.4021              | 0.3957             |
| Wind abandonment (MWh)           | 379                 | 13.5               |
| Photovoltaic abandonment (MWh)   | 4125                | 85.2               |
| Hydropower abandonment (MWh)     | 2154                | 7846               |

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