Research on clean energy complementary power generation and optimal operation in Yalong river basin

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Abstract: Based on the general situation and development status of Yalong river clean energy demonstration base, the typical wind power stations, PV power stations and hydropower stations in the downstream of Yalong river are selected for research. Firstly, the principle of wind power, photovoltaic power and hydropower complementarity was analyzed, and the complementary characteristics of this three kinds of power sources in a daily time scale were explored. Secondly, in order to maximize the consumption of clean energy, ensure the operation safety of the grid and protect the cascade hydropower benefits, a mathematical model was built with the objective of the minimum load tracking difference index and the minimum total amount of water abandoned in the dispatching period, which was solved by two-layer nested optimization solution. The results show that the cascade hydropower of Yalong river has the ability to regulate the fluctuation of wind power output in the basin. The three kinds of power supply bundled out can provide stable and high quality electricity for the grid. The last, a new strategy for cascade hydropower operation after complementation was proposed, which can promote the realization of low carbon power dispatching and the optimization of energy structure.

1. Introduction

Given the serious conditions of energy shortage and environmental pollution, the development and utilization of sustainable and clean energy source has become the focus of many countries. Since 2016, the National Energy Administration has strongly supported the Yalong River Company to build a multi-million-kilowatt clean energy demonstration base with wind power, photovoltaic (PV) power and hydropower complementation, which has led to a series of complex scientific engineering problems [1]. Among these problems, the joint planning of wind power, PV power and hydropower is one of the most important issue [2]. Wind power and PV power are greatly affected by meteorological factors and cannot be randomly scheduled, which are difficult to maintain a stable output [3]. To stabilize the impact of the
instability on the power grid, finding the adjustment and compensation "media" is an effective way to solve the problem of large-scale centralized power supply through wind power and PV [4, 5]. Pumped storage power stations are one option [6,7], but it has strict geographical condition requirements and limited storage capacity, which makes it not suitable for large-scale promotion. Batteries and biomass [8,9] have the same limitations, which are small in capacity and are only suitable for off grid/island hybrid power generation systems. Cascade reservoir hydropower station with regulating performance can solve the problem of geographical location and capacity limitation [10,11], and its own transmission channels can be used together with wind power and PV power, which can effectively promote the integration of wind power and PV power grids [12].

Based on the Yalong River Clean Energy Demonstration Base, this paper deeply explores the daily output complementation characteristics of the wind power, PV power and hydropower in different seasons and different meteorological conditions, and considers factors such as clean energy utilization, power grid operation safety and cascade hydropower discarded water, and construct multi-objective model. Then taking the minimum of load-tracking difference index and the minimum amount of discarded water during the scheduling period as the objective function, the improved particle swarm optimization algorithm (IPSO) and the bat algorithm (BA) are used to calculate the clean energy consumption, and a new complementary power generation optimization scheme that can ensure the safety of the grid operation is proposed.

2. Wind-PV-hydropower complementation principle and characteristics

2.1 Complementation principle

According to the output characteristics of wind power, PV and hydropower, the complementation characteristics can be summarized as hydropower compensates wind power and PV power by its power capacity, wind power and PV power compensate hydropower by their power output, and the complementation principle is shown in Figure 1.

1) Capacity compensation - mainly divided into volatility compensation and intermittent compensation. The volatility compensation is to eliminate the sawtooth fluctuation of wind power and photovoltaic output by quickly starting the unit's adjustment capability. The intermittent compensation is that compensating the output gap through the reservoir water storage based on the volatility compensation, resulting in a smooth and stable output process.

2) Output compensation - Hydropower is limited by runoff volume, and there is a difference between abundant and dry seasons during the year. Therefore, in the dry season, wind power and PVs can compensate for the shortage of hydropower. In addition, the reservoir has a water storage function, which can make full use of wind power and PV power generation during the day and increase hydropower output to compensate wind power and PV power at night or during peak load hours of the power grid.

Figure 1 Schematic diagram of wind-PV-hydropower complementarity
2.2 Complementation characteristics

The wind power, PV power and hydropower complementation characteristics have been thoroughly analyzed by the existing researches and will not be repeated here. The main conclusion is that wind power and PV power generates more energy in winter and spring, which can compensate the hydropower; The hydropower output is large in summer and autumn, which can compensate the wind power and PV power [1,6].

In a single day, since the three power generation methods are greatly affected by meteorological factors, in order to understand the complementation of these three methods of wind power, PV power and hydropower, it’s should also be considered that the impact of different weather. In this paper, 12 typical days combination of the four seasons and the weather of cloudy, sunny and rain (Table 1) were analyzed. The weather conditions are derived from historical statistics of the China Meteorological Administration. Three months each season, and March is the first month of spring. The operation data of the typical scenic hydropower station in the Yalong River Basin was selected and normalized to obtain the per-day output process of wind power, PV power and hydropower, as shown in Figure 2.

Under different weather of the same season, the change trend of PV output in 24 hours is basically the same, both are arch bridge type, the peak of output is sunny> cloudy> rainy day, the peak appearance time is basically the same, mainly affected by solar radiation, the greater the solar radiation, the greater the PV power output. However, the wind speed varies greatly under these three weather conditions, which leads to different trends in the wind power output process. The fluctuations are greatest on sunny days, the peak output is around 16 o'clock, the output trough is about 9 o'clock, and the wind power output on cloudy and rainy days is relatively large. The hydropower output did not change much in the same season.

| Typical days | Spring | Summer | Autumn | Winter |
|--------------|--------|--------|--------|--------|
| Cloudy       | C-SP   | C-S    | C-A    | C-W    |
| Sunny        | S-SP   | S-S    | S-A    | S-W    |
| Rainy        | R-SP   | R-S    | R-A    | R-W    |
In the same weather of different seasons, the PV power output process is basically the same, still in the arch type. The order of peak output in different season is winter>spring>autumn>summer, the peak appearance time is different, because the PV power output is not only affected by solar radiation, but also affected by temperature. The higher temperature, the smaller PV output. The wind power output is much larger in winter and spring than in summer and autumn. The hydropower output is just opposite to wind power and photoelectricity. The summer and autumn seasons are much larger than the winter and spring seasons.

In summary, the three power sources of wind power, PV power and hydropower have good complementarity under different weather conditions, among which the complementarity of spring and rain is better.

3. Wind-PV-hydropower complementary operation

3.1 Operation target
Different from off-grid hybrid power generation system, the Yalong River wind power, PV power and hydropower complementary power generation is a multi-million-kilowatt large-scale multi-power grid-connected complementary power generation. It must consider the safe and stable operation of the grid, that is, “point-to-point source-load matching”; in addition, wind power generation enjoys policy protection, it’s requires additional consideration of hydropower efficiency. Hydropower should not be sacrificed to compensate wind power and PV power fluctuations. After complementation adjustment, the cascade hydropower operation mode is bound to change. It is necessary to reformulate the economical and rational daily dynamic control plan for each reservoir.

3.2 Optimization method

3.2.1 mathematical model

(1) Objective function

The smaller the difference between the wind power and PV power water output process and the load curve, the better the safe and stable operation of the power system. Therefore, a mathematical model aiming at the minimum load tracking difference index of the wind power, PV power and hydropower complementary power generation system is established. The objective function 1 is as follows:

\[
\min K_r = m_1 D_u + m_2 D_v + m_3 D_w
\]

\[
D_u = \frac{1}{P_g} \sqrt{\frac{1}{T} \sum_{t=1}^{T} (P_{H,t} - P_{G,t})^2}
\]

\[
D_v = \sqrt{\frac{1}{T-1} \sum_{t=1}^{T} (P_{r,t} - \bar{P}_r)^2}
\]

\[
P_{r,t} = P_{G,t} - P_{H,t}
\]

\[
D_w = \frac{P_{r,max} - P_{r,min}}{T}
\]

Among them, \(K_r\) is the load tracking difference index, \(D_u\) is the actual output relative to the load fluctuation rate, \(D_v\) is the load fluctuation standard deviation, \(D_w\) is the load power change rate, \(T\) is the scheduling period, \(\bar{P}_G\) is the load average, \(P_{G,t}\) is the grid load during period \(t\), \(P_{H,t}\) is the actual total output of wind power, PV power and hydropower in period \(t\), \(P_{r,t}\) is the optimal load curve value for period \(t\), \(\bar{P}_r\) is the average value of optimized load curve, \(P_{r,max}\) and \(P_{r,min}\) are the maximum and minimum values of the optimized load curve, respectively, \(m\) is the weight coefficient of the corresponding index, and the weight coefficient can be adjusted according to the importance of each index.

In order to reduce the impact of complementary power generation on hydropower generation, an optimization model with the minimum amount of discarded water by cascade reservoirs during the dispatch period is established. The objective function 2 is formulated as follows:

\[
\min Q_q = \min \left[ \int_0^T q_t dt \right]
\]

Among them, \(Q_q\) is the total amount of discarded water at the end of the scheduled period of the cascade reservoir, and \(q_t\) is the amount of stepped discarded water in the period \(t\).

(2) Constraints

It mainly includes two categories. The first type of constraint is the power system constraint, and the second type of constraint is the constraint of the reservoir system itself.

(1) Power balance:

\[
N_{r,t} = N_{S,t} + N_{W,t} + \sum_{i=1}^{n} N_{i,t}
\]

Where: \(N_{r,t}\) is the total output of the system during the period \(t\); \(N_{S,t}\) is the PV output of the period \(t\); \(N_{W,t}\) is the wind power output of the period \(t\); \(N_{i,t}\) is the output of the \(i\)-th hydropower station during the period \(t\), \(n\) is the number of power stations.
(2) Electricity balance:
\[ \sum_{t=1}^{T} N_{t,t} \Delta t = \sum_{t=1}^{T} N_{S,t} \Delta t + \sum_{t=1}^{T} N_{W,t} \Delta t + \sum_{t=1}^{n} N_{i,t} \Delta t \]  
(8)

(3) Output fluctuations:
\[ |N_{t+1} - N_t| \leq \Delta N_T \]  
(9)

Where: \( \Delta N_T \) is the allowable value of the total output of the water-gloss wind complementation total output.

(4) Upper and lower limits of output:
\[ N_{S,t}^{\text{min}} \leq N_{S,t} \leq N_{S,t}^{\text{max}} \]  
(10)
\[ N_{W,t}^{\text{min}} \leq N_{W,t} \leq N_{W,t}^{\text{max}} \]  
(11)
\[ N_{i,t}^{\text{min}} \leq N_{i,t} \leq N_{i,t}^{\text{max}} \]  
(12)

Where \( N_{S,t}^{\text{max}}, N_{S,t}^{\text{min}} \) is the maximum and minimum value of PV output during period \( t \); \( N_{W,t}^{\text{max}}, N_{W,t}^{\text{min}} \) is the maximum value of wind power output during period \( t \) The minimum value; \( N_{i,t}^{\text{max}}, N_{i,t}^{\text{min}} \) is the maximum and minimum values of the \( i \)-th hydropower station output during the period \( t \).

(5) Water balance constraint:
\[ V_{i,t+1} = V_{i,t} + (Q_{r,i,t} - Q_{o,i,t} - S_{i,t}) \Delta t \quad \forall t \in T \]  
(13)

Where: \( V_{i,t+1} \) is the water storage capacity of the \( i \)-th reservoir at the end of the period \( t \) (m\(^3\)); \( V_{i,t} \) is the water storage capacity of the \( i \)-th reservoir at the beginning of the period \( t \) (m\(^3\)); \( S_{i,t} \) is the discarded water flow rate (m\(^3\)/s) of the \( i \)-th reservoir in the period \( t \).

(6) Flow balance constraint:
\[ Q_{r,i+1,t} = Q_{r,i,t} + q'_{i,t} \]  
(14)

Where: \( q'_{i,t} \) is the inflow of the \( t \) interval of the \( i \)-th and \((i+1)\)th libraries (m\(^3\)/s);

(7) Capacity constrain:
\[ V_{i,t}^{\text{min}} \leq V_{i,t} \leq V_{i,t}^{\text{max}} \]  
(15)

Where: \( V_{i,t}^{\text{max}}, V_{i,t}^{\text{min}} \) are the maximum and minimum value (m\(^3\)) of the reservoir capacity during the period \( t \) of the \( i \)-th reservoir; \( V_{i,t} \) is the amount of water stored in the \( i \)-th reservoir of the period \( t \) (m\(^3\));

(8) Water level constraint:
\[ Z_{i,t}^{\text{min}} \leq Z_{i,t} \leq Z_{i,t}^{\text{max}} \]  
(16)

Where: \( Z_{i,t}^{\text{max}}, Z_{i,t}^{\text{min}} \) are the maximum and minimum value of the reservoir water level in the \( i \)-th reservoir of period \( t \) (m); \( Z_{i,t} \) is the period \( t \) The water level of the \( i \)-th reservoir (m).

(9) Discharge flow restriction:
\[ Q_{l,t}^{\text{min}} \leq Q_{l,t} \leq Q_{l,t}^{\text{max}} \]  
(17)

Where: \( Q_{l,t}^{\text{min}}, Q_{l,t}^{\text{max}} \) is the minimum and maximum value (m\(^3\)/s) of the reservoir discharge in the period \( t \) of the \( i \)-th power station.

(10) Minimum starting output:
\[ (N_{i,t} - N_{\text{min}_i})N_{i,t} \geq 0 \]  
(18)

In the formula; \( N_{\text{min}_i} \) is the minimum operating output of the \( i \)-th power station.

### 3.2.2 Model solving

The basic idea of solving the model is two-layer nesting optimization, that is, the nested cascade hydropower scheduling layer of the wind power, PV power and hydropower complementary power generation layer, each layer follows its own objective function. Firstly, determine the output of each period of wind power, PV power and hydropower in one day, ensure that the power output process and the grid load
curve are highly matched to meet the objective function 1; secondly, the total generating capacity of cascade hydropower stations is allocated to each power station, and the operating scheme of cascade hydropower stations is determined to satisfy the objective function 2.

The wind power, PV power and hydropower complementary power generation layer is solved by the IPSO algorithm [4], and the total hydropower output curve of the cascade hydropower with the minimum load tracking difference index $K_r$ is obtained. Then the bat algorithm is used to calculate the optimal operation scheme of cascade hydropower under the condition of the minimum amount of discarded water. The algorithm flow chart is shown in Figure 3.

![Figure 3 Flow chart of the model algorithm](image)

### 3.3 Case study

#### 3.3.1 Data selection

According to the planning progress of the Yalong River Basin Wind power and PV power Water Complementation Clean Energy Demonstration Base, the long-term horizontal year 2025 is selected to consider the power generation situation after the completion of the wind power, PV power and hydropower Station. 74 wind power stations, 26 PV power plants and 5 downstream hydropower stations were selected, and the wind and light power stations were treated equivalently to form a 12600MW wind power
station and 181600MW PV power station. According to the results of section 2.2 complementation characteristics analysis, four typical weather types, R-SP, R-S, S-A, and S-W are selected for optimization calculation.

3.3.2 Result analysis
(1) Optimize scheduling results
After substituting the typical daily data into the model calculation, the optimization results are shown in Table 2, and the wind-light-water complementary power generation process is shown in Fig. 4. The results show that the optimal wind and water hybridization scheduling model constructed by this paper can make full use of the complementation characteristics of power supply, exert the powerful adjustment ability of cascade hydropower, effectively stabilize the fluctuation of wind and output, and provide safe and stable power output for the grid. The best is RW, the load tracking difference index $K_r$ is 85.96; the S-A has the largest amount of discarded water, which is 10.918 million $m^3$, and the amount of discarded water in the dry season is 0 $m^3$.

| Typical days | S-SP | R-S | S-A | R-W |
|-------------|------|-----|-----|-----|
| $K_r$       | 91.15| 87.23| 88.91| 85.96|
| $Q_q$ ($10^4 m^3$) | 0 | 574.6 | 1091.8 | 0 |

Table 2 The optimal dispatching results of wind-PV-hydropower complementary power generation

(2) Analysis of the influence of weight coefficient
The initial values of the weighting factors $m_1$, $m_2$ and $m_3$ of the load-following difference index are set to 1:1:1. To analyze the influence of different weight combinations on the optimization results, the typical days of S-A are selected, and two control groups are set up, which are changed from a single weight. The double weight changes were compared, and the results are shown in Table 3.
When $m_1$, $m_2$, and $m_3$ have a value of 4:4:1, the optimization result is the best and the amount of discarded water is the smallest. It can be seen from the table that when a single weight changes, the corresponding index has the greatest impact, the weight increases, and the corresponding index value decreases, while the other two indicators are slightly increased. When the dual weight changes, the corresponding two indicators are reduced, and the effect is better than the single weight change. However, the increase in weight is not as large as possible. After a certain critical point, the indicator will begin to deteriorate. Among the three values of $D_u$, $D_v$, $D_w$, $D_u$ has the greatest influence on the amount of discarded water, but in general, the change of the weight coefficient has little effect on the optimization result.

| $m_1$ | $m_2$ | $m_3$ | $D_u$  | $D_v$  | $D_w$  | $Q_q$  |
|-------|-------|-------|--------|--------|--------|--------|
| 0.33  | 0.33  | 0.33  | 0.138  | 230.228| 36.372 | 1091.8 |
| 0.5   | 0.25  | 0.25  | 0.135  | 237.371| 36.624 | 1091.4 |
| 0.66  | 0.17  | 0.17  | 0.131  | 234.199| 36.843 | 1089.8 |
| 0.8   | 0.1   | 0.1   | 0.137  | 234.514| 36.875 | 1093.5 |
| 0.25  | 0.5   | 0.25  | 0.138  | 227.964| 37.159 | 1091.4 |
| 0.17  | 0.66  | 0.17  | 0.138  | 220.356| 38.943 | 1089.9 |
| 0.1   | 0.8   | 0.1   | 0.138  | 235.772| 39.357 | 1091.7 |
| 0.25  | 0.25  | 0.5   | 0.138  | 236.205| 34.081 | 1091.5 |
| 0.17  | 0.17  | 0.66  | 0.138  | 243.181| 33.774 | 1091.4 |
| 0.1   | 0.1   | 0.8   | 0.138  | 255.482| 36.055 | 1092.1 |
| 0.33  | 0.33  | 0.33  | 0.139  | 227.991| 33.087 | 1091.4 |
| 0.2   | 0.4   | 0.4   | 0.139  | 204.662| 32.591 | 1089.3 |
| 0.11  | 0.44  | 0.44  | 0.139  | 229.045| 36.367 | 1092.3 |
| 0.06  | 0.47  | 0.47  | 0.133  | 226.452| 35.247 | 1091.5 |
| 0.4   | 0.4   | 0.2   | 0.129  | 200.393| 37.315 | 1087.4 |
| 0.44  | 0.44  | 0.11  | 0.137  | 205.582| 37.588 | 1091.7 |
| 0.47  | 0.47  | 0.06  | 0.137  | 233.112| 33.806 | 1091.6 |
| 0.4   | 0.2   | 0.4   | 0.135  | 230.847| 32.144 | 1089.1 |
| 0.44  | 0.11  | 0.44  | 0.138  | 232.525| 35.322 | 1091.9 |

(3) Analysis of reservoir operation plan

The complementation of wind power, PV power and water will have a certain impact on the cascade hydropower operation. The comparison of reservoir water level changes before and after complementation is shown in Figure 5.

In the dry season, the power station water level before the complementation showed a downward trend. After the complementation, the water level of the primary and secondary power stations of Jinping showed an upward trend, and the decline of other power stations decreased. During the wet season, the water level of the power station showed an upward trend, except for the Longtou reservoir of Jinping primary hydropower station, the increase range of the water level in other power stations increases. The water level change of Tongzilin Power Station is quite chaotic. The main reason is that the power station is at the end of the cascade and there is no reservoir for itself, resulting poor adjustment ability.

After the wind power, PV power and hydropower complement each other, the inter-plant load should be reasonably distributed, and the reservoir with stable regulation and storage capacity should be used to stabilize the output fluctuation, and the daily regulating power station should be driven to cope with the peak stage power generation task; the water abundance during the wet season is most likely to occur in the cascade downstream power station, which can increase the power generation capacity of the downstream power station appropriately, and the upstream regulating power station undertakes part of the water storage task within the safe range; there is no water discarded in the dry season, the cascade...
energy storage can be pre-increased, and the water level storage capacity of the upstream regulated power stations should be appropriately increased, while the downstream power stations should undertake more power generation tasks.

4. Conclusion
Based on the analysis of the daily complementarity of wind power, PV power and hydropower in different seasons, this paper establishes a multi-objective mathematical model considering clean energy consumption and grid operation safety and simulates the calculation process of wind-water complementation power generation. The results show that the Yalong River basin cascades. Hydropower can adjust the fluctuation of wind power output. After complementary adjustment, it can provide stable high-quality power for the power grid. In addition, the complementation wind power and PV power water has a greater impact on the operation of cascade hydropower, and the water level rises obviously, so as to reduce the amount of discarded water as much as possible. It is suggested that the upstream reservoir power station will undertake more tasks for adjustment and storage, and the downstream flow-through
power station will undertake more power generation tasks. This paper mainly makes up for the shortcomings and gaps in the previous research on large-scale wind power, PV power and cascade hydropower grid-connected power generation operation in the same basin, but it simplifies the wind and solar energy constraints, and does not consider the abandonment of wind and solar energy. The follow-up study will consider the more complicated and comprehensive problem of multi-energy complementary power generation optimization scheduling.

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