Coupling optimization model of hydropower station power dispatching based on complex dispatching constraints and cascade joint commissioning

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Abstract—In order to increase the average power generation of a hydropower station and reduce its water consumption, this paper proposes a hydropower dispatching coupling optimization model based on complex dispatch constraints and cascade-connected dispatching. The power generation water consumption and the remaining load of the power grid are used as the objective function to construct a power dispatch coupling optimization model. After all the constraints are met to solve the objective function, the improved genetic algorithm and the coupling constraint adjustment strategy are combined to form a hybrid search method to realize the genetic operation. The strategy is improved to complete the optimization of power dispatch. The experimental results show that the above model can effectively realize the optimization of power dispatch and increase the average power generation of hydropower stations. It is hoped that the model can reasonably optimize the power dispatch during the flood season and the dry season, thereby effectively reducing the water consumption of the cascade and increasing the power generation of the cascade.

1. Introduction

The tasks of cascade hydropower stations are power generation, flood control, water supply, etc., and its dispatch operation belongs to a multi-objective optimization problem [1], which leads to a very complicated process of constructing and solving the optimization model of cascade hydropower station dispatching. However, the complex power and hydraulic dispatching requirements further increase the difficulty of model construction and solution [2]. In which the requirements of hydropower dispatching are load tracking response, power grid security and stability control, flood control and ecological flow, etc. At present, accurately depicting project requirements has become a major problem in hydropower dispatching [3,4].

Many scholars have launched research on this issue. Literature [5] and others designed a short-term optimal dispatch model based on the principle of spatial mapping for reservoirs and hydropower
stations. According to the spatial mapping principle, the linear mapping relationship between the upstream and downstream inbound and outbound flows is obtained, so as to construct a short-term optimal dispatch model of cascade reservoirs considering the water flow lag, and realize the control and dispatch of hydropower resources. However, the linear mapping process applied by this model can only achieve a certain range of morphisms in a given domain, which leads to a large overall water consumption and low practicability. Literature [6] and others designed a short-term optimal scheduling model for the cascade hydro-power generation system, and built a mixed-integer linear programming model with the goal of minimizing the water consumption of the cascade hydropower system to improve the execution of the scheduling plan of the combined power generation system. However, this model only considers the minimum water consumption, which leads to its poor ideal level of average power generation.

Meanwhile, as the scale of hydropower station groups continues to increase, the difficulty of solving optimal dispatching of hydropower stations has also increased [7], and the above-mentioned methods can no longer meet the optimization needs of hydropower dispatching. Therefore, to solve the problems of low average power generation and high water consumption in traditional models, this paper studies a hydropower dispatching coupling optimization model based on complex dispatching constraints and cascade-connected dispatching in order to increase the average power generation of hydropower stations.

2. Coupling optimization model of power dispatch for hydropower station

2.1. Objective function

Taking into account the power dispatch characteristics of hydropower stations, the power consumption of power generation and the remaining load of the grid are used as the objective function to construct a coupling optimization model for power dispatching of hydropower stations.

The water consumption of a hydro-generator refers to the total amount of water flowing through the pressure diversion pipe of the hydro-generator set, which does not include the water consumption caused by start up and shutdown. The installed capacity of the cascade hydropower station in this study is 4.5 million kW, and the unit is composed of water turbines, generators, governors, excitation systems, cooling systems, and power station control equipment. The formula for generating water consumption \( W_{j,t} \) per unit time of unit \( j \) is as follows:

\[
W_{j,t} = Q_{j,t} \times \frac{\pi D_j^2 v_{j,t}}{4}
\]  

(1)

Where the power generation flow of unit \( j \) of the cascade hydropower station at time \( t \) is \( Q_{j,t} \); the diameter of the inlet of the pressure diversion pipe is \( D_j \); the speed of the water outlet of the turbine at time \( t \) is \( v_{j,t} \).

Take the power generation water consumption of cascade hydropower stations with \( M \) hydropower station reservoirs and the remaining load of the power grid as the objective function. In the operation period \( T \), the water consumption \( W \) for power generation is minimized and the remaining load is the smallest. A coupling optimization model for hydropower dispatching is constructed, the formula is as follows:
Where the remaining load of the power grid is $F$; the output of the cascade hydropower station during the $t$ period is $G_{j,t}$, and the period number is $t$, $t = 1, 2, \cdots, T$; the hydropower station number is $j$, $j = 1, 2, \cdots, M$; the average output of the cascade hydropower station $j$ during the $t$ period is $G_{j,t}$.

Under the same control conditions, it is based on two objective functions of power generation water consumption and grid residual load. A hydropower station dispatching coupling optimization model is constructed based on complex dispatching constraints and cascade-connected dispatching. The water level change process of the cascade hydropower station group is judged to minimize the power generation water consumption of the cascade hydropower station during the dispatch period and the minimum remaining load of the system, it can ensure that the dispatch plan meets the peak shaving demand [8,9].

### 2.2. Constraints

Hydroelectric power generation converts the gravitational potential energy of water into mechanical energy through a hydraulic turbine unit, so that the hydraulic turbine drives the hydraulic turbine generator to rotate and output electrical energy. On the basis of the above design objective function, the constraint conditions when solving the objective function are analyzed, and the content is as follows:

1. The water balance equation is as follows:

   $V_{j,s+1} = V_{j,t} + 3600 \left( Q'_{j,t} - C_{j,t} \right) \Delta t$ (3)

   $C_{j,t} = Q_{j,t} + d_{j,t}$ (4)

   Where the storage capacity of cascade hydropower station $j$ at time $t$ is $V_{j,t}$; the inflow flow of cascade hydropower station $j$ at time $t$ is $Q'_{j,t}$; the outflow flow of cascade hydropower station $j$ at time $t$ is $C_{j,t}$; the generation flow of cascade hydropower station $j$ at time $t$ is $Q_{j,t}$; The discarded water volume of hydropower station $j$ at time $t$ is $d_{j,t}$.

2. The water consumption for power generation of a hydropower station is restricted as

   $W_{j,t} \leq W_{j,t} \leq \bar{W}_{j,t}$ (5)

   Where the allowable minimum value of the total power generation water consumption of the cascade hydropower station $j$ at time $t$ is $W_{j,t}$; the maximum allowable value of the total power generation water consumption of the cascade hydropower station $j$ in the regulation period $T$ is $\bar{W}_{j,t}$.

3. The upper and lower constraints of power station output are
\[ G_{j,t} \leq \bar{G}_{j,t} \leq \bar{G}_{j,t} \]

Where the minimum allowable average output of cascade hydropower station \( j \) at time \( t \) is \( \overline{G}_{j,t} \); the maximum allowable average output of cascade hydropower station \( j \) at time \( t \) is \( \bar{G}_{j,t} \);

(4) The upper and lower constraints of reservoir capacity are

\[ V_{\text{min},j,t} \leq V_{j,t} \leq \overline{V}_{j,t} \]

Where the lower limit of the reservoir water level of cascade hydropower station \( j \) is \( V_{\text{min},j,t} \), which is the minimum water level required for comprehensive utilization; the upper limit of the reservoir water level of cascade hydropower station \( j \) is \( \overline{V}_{j,t} \), that is, the normal reservoir water level in non-flood seasons, which is the flood control limit water level during the flood season.

(5) The output climbing constraint is

\[ \left| G_{j,t} - G_{j,t+1} \right| \leq \Delta G_{j} \]

The upper limit of the output change range of the cascade hydropower station \( j \) at adjacent moments is \( \Delta G_{j} \), which the output change range of the cascade hydropower station at the adjacent time is limited.

(6) The constraints of the water velocity and power generation flow at the outlet of the turbine are

\[
\begin{cases}
    V_{\text{min},j,t} \leq v_{j,t} \leq \overline{V}_{j,t} \\
    Q_{\text{min},j,t} \leq Q_{j,t} \leq \overline{Q}_{j,t}
\end{cases}
\]

Where the lower limit of the flow velocity at the outlet of the pressure diversion pipe of the cascade hydropower station \( j \) at time \( t \) is \( v_{\text{min},j,t} \); the upper limit of the flow velocity at the outlet of the pressure diversion pipe of the cascade hydropower station \( j \) at time \( t \) is \( \overline{V}_{j,t} \); the lower limit of power generation flow of cascade hydropower station \( j \) at time \( t \) is \( Q_{\text{min},j,t} \); the upper limit of the outbound flow of cascade hydropower station \( j \) at time \( t \) is \( \overline{Q}_{j,t} \).

(7) The constraint of outbound flow is

\[ C_{\text{min},j,t} \leq C_{j,t} \leq \overline{C}_{j,t} \]

Where the lower limit of power generation flow of cascade hydropower station \( j \) at time \( t \) is \( C_{\text{min},j,t} \); the upper limit of power generation flow of cascade hydropower station \( j \) at time \( t \) is \( \overline{C}_{j,t} \).

(8) The constraints of the beginning and end water levels are
where the initial water level control value of the cascade hydropower station \( j \) at time \( t \) is \( Z_{j, t}^{\text{beg}} \), that is, the starting water level during the operation period of the reservoir scheduling. The expected final water level control value of the cascade hydropower station \( j \) at time \( t+1 \) is \( Z_{j, t+1}^{\text{end}} \), which is the expected target during the operation period of the reservoir dispatch.

3. Solving the optimization model

3.1. Adjustment strategy for coupling constraints

The individuals with constraint destruction in the population are corrected, it includes the constraint destruction for power generation water consumption, outbound flow, and output [10-11].

Taking \( t=1 \) as the initial time, it is necessary to search one by one until the end of the scheduling period. The water level at the end of the time is adjusted when the constraint is violated according to the following strategy, it can ensure that the power generation water consumption at each time is within the constraint range. The adjustment strategy is as follows:

\[
W'_{j, t} = \begin{cases} 
\bar{W}_{j, t}, & W_{j, t} \geq \bar{W}_{j, t} \\
W_{j, t}, & W_{j, t} < \bar{W}_{j, t}
\end{cases}
\]  
\tag{12}

\[
V'_{j, t+1} = V_{j, t} - 3600W'_{j, t} \Delta t
\]  
\tag{13}

\[
Z'_{j, t+1} = f \left( V'_{j, t+1} \right)
\]  
\tag{14}

Where the relationship curve of water level storage capacity is \( f(\cdot) \); the adjusted water consumption for power generation is \( W'_{j, t} \); the final storage capacity at the adjusted time is \( V'_{j, t+1} \); the adjusted reservoir expected final water level is \( Z'_{j, t+1} \).

Taking \( t=1 \) as the initial time, it is necessary to search one by one until the end of the scheduling period. The water level at the end of the time is adjusted when the constraint is violated according to the following strategy, it can ensure that the outbound flow at each time is within the constraint range. The adjustment strategy is as follows:

\[
C'_{j, t} = \begin{cases} 
\bar{C}_{j, t}, & C_{j, t} \geq \bar{C}_{j, t} \\
C_{j, t}, & C_{j, t} < \bar{C}_{j, t}
\end{cases}
\]  
\tag{15}

\[
V'_{j, t+1} = V_{j, t} - 3600 \left( Q'_{j, t} - C'_{j, t} \right) \Delta t
\]  
\tag{16}

\[
Z'_{j, t+1} = f \left( V'_{j, t+1} \right)
\]  
\tag{17}
Where the relationship curve of water level storage capacity is \( f(\cdot) \); the adjusted outbound flow is \( C'_{j,t} \); the final storage capacity at the adjusted time is \( V'_{j,t+1} \); the adjusted reservoir expected final water level is \( Z'_{j,t+1} \).

In order to make the output at each moment conform to the upper and lower limits of the output at this moment, it must also conform to the output climbing constraints at the adjacent moments. The intersection of force upper and lower limit constraints and output climbing constraints can be extracted by formula (19) to form the same constraint. The formula of formula (18) is as follows:

\[
\begin{align*}
G'_{j,t} &= \max \left( G_{j,t-1} - \Delta G_{j,t}, G_{j,t} \right) \\
G'_{j,t} &= \min \left( G_{j,t-1} + \Delta G_{j,t}, G_{j,t} \right)
\end{align*}
\] (18)

Taking \( t=1 \) as the initial time, it is necessary to search one by one until the end of the scheduling period. The water level at the end of the time according to the following strategy is adjusted, which can ensure that the output constraints at each time are within the constraints. The adjustment strategy is as follows:

\[
\begin{align*}
G_{j,t} &= \begin{cases} 
G'_{j,t}, & G_{j,t} > G'_{j,t} \\
G_{j,t}, & G_{j,t} < G'_{j,t}
\end{cases} \\
W_{j,t} &= F \left( G_{j,t}, G_{j,t} \right) \\
C_{j,t} &= F \left( G_{j,t}, G_{j,t} \right) \\
V_{j,t+1} &= V_{j,t} - 3600W_{j,t} \Delta t \\
V_{j,t+1} &= V_{j,t} - 3600 \left( Q'_{j,t} - C_{j,t} \right) \Delta t \\
Z_{j,t+1} &= F \left( V_{j,t+1} + V_{j,t+1} \right)
\end{align*}
\] (19-24)

Where the power generation water consumption after adjustment of output constraint is \( W_{j,t} \); the outbound flow after adjustment of output constraint is \( C_{j,t} \); the end storage capacity of the period after adjustment of output constraint is \( V_{j,t+1} \) and \( V_{j,t+1} \); the expected end water level of the reservoir after adjustment of output constraint is \( Z_{j,t+1} \). After adjustment, the actual output \( G_{j,t} \) that can be achieved by the power generation water consumption \( W_{j,t} \) and the outbound flow \( C_{j,t} \) is close to the expected output \( G_{j,t} \), and the code block is \( F(\cdot) \).

3.2. Improved genetic operation strategy

The genetic algorithm is facilitated to solve the model, its basic principle is divided into three steps. The specific content is as follows:
Step 1: For the water level at a certain moment, an initial population is randomly generated. After non-dominant sorting, genetic manipulation is used to obtain the first generation population.

Step 2: At the beginning of the second generation, the parent population and the offspring population are integrated. After non-dominated sorting, the crowded distance of each level of individuals is calculated, and the non-dominated relationship and the crowded distance of individuals are comprehensively considered to select reasonable individuals. A new population is established to determine the water flow out of the reservoir at different times.

Step 3: A new generation of populations is formed based on genetic operations, and calculations are repeated. Finally, the optimal solution is obtained, which is the optimal water flow.

Because the traditional genetic algorithm has the problems of low average power generation and large water consumption, the genetic operation strategy is optimized and improved. There are three operations in genetic operations: selection, crossover, and mutation. The use of full probability selection operators, arithmetic crossover operators and directional mutations can complete genetic operations, reduce the damage of individual coupling constraints, ensure population diversity [12], and determine the optimal water flow.

The full-probability selection operator selects the optimal individual after completing the fitness value calculation and the non-dominated hierarchical sorting, that is, the optimal water output at a certain moment. Then, the optimal individual is put into the next generation to ensure that the population has a feasible solution during evolution, through continuous iteration of the optimal water output at different times [13,14].

3.3 The overall framework of the optimization model

Genetic algorithm and multiple constraint adjustment strategies are coupled to form a hybrid search method. The overall framework of the hydropower dispatching coupling optimization model based on complex dispatching constraints and cascade-connected dispatching is solved, as shown in Figure 1 [15].

![Figure 1 The overall solution framework of the optimization model](image-url)
In Figure 1, the design of the coupling constraint adjustment strategy is completed through power generation water consumption constraints, outbound flow constraints, and output constraints. Secondly, adopt the initial population and coupling constraint adjustment strategy to determine the water consumption target and peak shaving target. Through non-dominant hierarchical sorting and genetic operations, the crowding distance is calculated to determine the termination condition, and the output result obtained is a multi-objective hybrid search. The improved genetic algorithm finally realizes operations such as full probability selection, arithmetic crossover and qualitative mutation.

4. Experimental analysis

In order to verify the effectiveness of the above-mentioned hydropower dispatching coupling optimization model based on complex dispatching constraints and cascade-connected dispatching, the following experiments are designed. The cascade hydropower station of the Jinguang Power Group in the Yalong River Basin was selected as the experimental object. The river where the cascade hydropower station is located has a total length of 1148km, a drainage area of 89,000 km², and a multi-year average water volume of 54.5 billion m³. Its drainage basin has a natural drop of 2235m. In which there are 7 hydropower stations, namely Yangfanggou Hydropower Station, Karaxiang Hydropower Station, Jinping I Hydropower Station, Jinping II Hydropower Station, Guandi Hydropower Station, Ertan Hydropower Station, Tongzilin Hydropower Station, with a total installed capacity of 8426MW. The Jinping I Hydropower Station and the Ertan Hydropower Station belong to multi-year regulating reservoirs, and there is a good hydropower compensation function in the optimal power dispatch of cascaded hydropower stations. Karaxiang Hydropower Station and Yangfanggou Hydropower Station are incomplete annual regulating reservoirs. Jinping II Hydropower Station, Tongzilin Hydropower Station and Guandi Hydropower Station belong to daily regulating reservoirs. The basic data of the province's cascade hydropower stations are shown in Table 1.

| Hydropower station       | Tuning performance | Installed capacity/ten thousand kW | Adjust storage capacity/100 million m³ | Designed annual power generation/100 million kW·h | Guaranteed output/MW | Normal high water level /m | Dead water level /m |
|--------------------------|--------------------|-----------------------------------|---------------------------------------|-----------------------------------------------|----------------------|--------------------------|----------------------|
| Jinping I Hydropower Station | Years of adjustment | 360                               | 66.00                                 | 16.69                                         | 169.1                | 1250                     | 1187                 |
| Karaxiang Hydropower Station | Incomplete annual adjustment | 108                               | 1.50                                  | 29.69                                         | 110                  | 980                      | 947                  |
| Jinping II Hydropower Station | Annual adjustment | 480                               | 3.80                                  | 21.22                                         | 177.9                | 848                      | 833                  |
| Yangfanggou Hydropower Station | Incomplete annual adjustment | 150                               | 2.70                                  | 42.51                                         | 265                  | 770                      | 731                  |
| Ertan Hydropower Station | Years of adjustment | 330                               | 94.40                                 | 97.93                                         | 757.5                | 640                      | 596                  |
| Tongzilin Hydropower Station | Daily adjustment | 60                                | 2.30                                  | 41.75                                         | 356.2                | 450                      | 442                  |
| Guandi Hydropower Station | Daily adjustment | 24                                | 3.00                                  | 46.63                                         | 333.9                | 376                      | 364                  |
In order to solve the conflict between power generation water consumption and the remaining load of the grid in the objective function of cascade hydropower stations, a reserve capacity module is designed to store the excess power load, so as to achieve a balanced treatment between the power generation water consumption and the remaining load of the grid.

According to the hydropower station data in Table 1, the experiment was carried out on the Matlab simulation platform. Using the model in this paper, the model in the literature [5], and the model in the literature [6], a one-year power dispatch optimization of cascade hydropower stations is implemented. The literature [5] model is a short-term optimal dispatching model for reservoir groups based on the principle of spatial mapping; the literature [6] model is a short-term optimal dispatching model for a cascade hydro-electric power generation system. The scheduling optimization results of the three models are shown in Table 2. The differences between the model optimization results in this paper and the design results of cascade hydropower stations are shown in Table 3.

### Table 2 Scheduling optimization results of the three models

| Hydropower station | Our model | literature [5] | literature [6] |
|--------------------|-----------|----------------|----------------|
|                    | Average monthly power generation/100 million kWh | Guaranteed output/MW | Water consumption/100 million m³ |
| Jinping I Hydropower Station | 2.49 | 18.47 | 90.21 |
| Karaxiang Hydropower Station | 3.95 | 23.55 | 87.12 |
| Jinping II Hydropower Station | 2.39 | 19.82 | 85.56 |
| Yangfanggou Hydropower Station | 4.98 | 29.29 | 86.56 |
| Ertan Hydropower Station | 8.99 | 77.32 | 82.89 |
| Tongzilin Hydropower Station | 5.51 | 34.99 | 86.45 |
| Guandi Hydropower Station | 5.59 | 39.28 | 85.25 |
| Cascade | 34.3 | 242.72 | 480.89 |
According to Table 2 and Table 3, all three models can increase the average monthly power generation. Compared with the revised value of the monthly average power generation of the cascade, the model in this paper is increased by 14.9%, and the other two models are increased by 1.7% and 2.1% respectively compared with the revised value of the monthly average power generation of the cascade. The guaranteed output of the steps determined by the three models has been improved. The comparison between the model in this paper and the cascade guaranteed output design value increased by 11.8%, and the comparison between the other two models and the cascade guaranteed output design value increased by 8.6% and 6.5%, respectively. Experiments show that the model in this paper can effectively achieve power dispatch optimization, and the optimization results are significantly better than the other two models.

In order to further verify the rationality of the model in this paper, two hydropower stations, Jinping I Hydropower Station and Ertan Hydropower Station, are selected. The model in this paper is used to optimize the power dispatching, and the average monthly inbound flow and annual power generation are the mixed dispatch targets to calculate the water level and output process of the two
hydropower stations during the dispatch period. Figure 2 and Figure 3 respectively show the output process and water level of the two hydropower stations during the dispatch period.

![Figure 2 The output process of the two hydropower stations during the dispatch period](image1)

According to Figure 2 and Figure 3, it can be seen that Jinping I Hydropower Station and Ertan Hydropower Station belong to multiyear regulating reservoirs. During the flood season (April to September), the water can be fully stored to raise the water level, and compensation will be implemented in the dry season to meet the minimum output demand of the system. Because the Jinping I Hydropower Station and Ertan Hydropower Station are located at different steps, the output process and water level of the two hydropower stations are also different. Jinping I Hydropower Station is a leading power station. The reservoir needs to be vacated before the arrival of the flood season to reduce the water level to a minimum. After entering the flood season, as the incoming water increases, it gradually rises to the highest water level. The dry season needs to use its step compensation adjustment function. Ertan Hydropower Station always maintains stable water storage during the flood season, and maintains high water level operation during the dry season, so that the water consumption of the cascades is reduced, which can increase the power generation of the cascades and ensure the control of the energy storage of the cascades. The experimental results show that the model in this paper can reasonably optimize the power dispatch during the flood season and the dry season, effectively reduce the water consumption of the cascade, and increase the power generation of the cascade.

5. Conclusion

In order to reduce water consumption and improve the optimization problem of power dispatching,
this paper proposes a hydropower dispatching coupling optimization model based on complex dispatch constraints and cascade joint dispatching. The optimization of power dispatch of cascade hydropower stations is related to electric power and hydraulic power, and it belongs to a nonlinear programming problem with complex dispatch constraints. A multi-objective constraint function is constructed, and an improved genetic algorithm is combined with a coupling constraint adjustment strategy to solve it. Experiments with cascade hydropower stations on the Yalong River show that the model effectively increases the average power generation and reduces the water consumption of the cascades. In future research, it is necessary to further in-depth research on the cooperation ability of frequency modulation between hydropower units and thermal power units of cascade hydropower stations to enhance market competitiveness.

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