Research on the Hydropower Coupling-Based Hydropower Station Scheduling Optimization Model

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Abstract: In order to improve hydropower availability and give full play to its power generation capacity, it is of great significance to set up a feasible and efficient scheduling optimization model. Based on the hydropower output match relation, the coupling factor and coupling are put forward. These two notions will be taken as the restriction condition. The hydropower station scheduling optimization model has been established by taking the minimal deviation of fulfillment of sales objective as the target function. Based on example of Dagangshan hydropower station in the Dadu River area, the model algorithm of particle swarm optimization algorithm is used for validation. According to the empirical study, the model doesn't produce discarded water during power generation, compared with the comparison schedule. Besides, it has more daily power output and smaller deviation of daily sales target power generation, which can effectively guide the economic operation of Dagangshan hydropower station.

1. Introduction
China has abundant water resources. Its water energy resource reserve ranks No.1 in the world. China boasts seven major river basins and tens of thousands of rivers, containing huge available water energy resources. Over-40-year development of reform and opening, China already built 13 hydropower bases. The construction of these hydropower bases greatly promotes the cascading development of China's water resources, resources optimization and economic development in west China. As China's hydropower station group becomes bigger and develops rapidly, scholars focus more on how to optimize scheduling of hydropower station group, give full play to its power generation capacity and obtain more economic benefits. However, the hydropower station scheduling optimization is multi-phased, nonlinear and dynamic, and it's very complex to get an appropriate solution.

At present, the experts and scholars have conducted in-depth research on the optimization scheduling of hydropower stations. In the document [1], an optimal model is established to maximize power generation. By taking into account the water flow evolution, the MSDP method is used for model solution, significantly increasing the power generation of the hydropower station. In the document [2], the power generation maximum model with the guaranteed output is established to determine the reservoir level control method with different water intake frequency. The document [3] presents that the complex hydropower conversion relation is turned into the nonlinear relationship of a single variable,
and the optimization scheme is drawn through nonlinear planning solution. The document \cite{4} shows that a nonlinear optimization algorithm is introduced to convert non-convex and nonlinear problems into convex and linear problems, and get the optimal solution of the hydropower station scheduling optimization model. In the document \cite{5}, a mixed integer nonlinear programming model based on daily load optimization distribution is established, and the calculation result also verifies the model feasibility.

Therefore, the research on hydropower station scheduling optimization mainly focuses on the establishment of the target function conforming to the actual engineering need or the adoption of a more efficient model solution, etc. Based on the research on the traditional hydropower station scheduling optimization, to characterize and quantify the matching of hydropower station input and output, the hydropower coupling factor and level is proposed. By taking it as a restriction condition, the hydropower station scheduling optimization model based on hydropower coupling is established to effectively enhance the hydropower station water energy availability and power generation capacity.

2. Scheduling Optimization Modeling

Coupling is originally a physical concept. It represents the close cooperation and interaction between the input and output of multiple circuit elements and a process of transferring energy from one side to the other. Generally speaking, coupling is to describe the level of interdependence and interaction between different variables in a certain system \cite{6}. In order to characterize and quantify the hydropower station output match in time and space, the hydropower coupling factor is proposed herein. The hydropower coupling factor is expressed as the function of non-actual energy storage value and the allowed maximum energy storage value in a certain period. Besides, the non-actual energy storage value in a certain period is associated with the reservoir’s actual energy storage value, intake water and power generation. Therefore, the hydropower coupling factor may reflect whether the individual hydropower station output matches in time sequence. The coupling factor calculation formula is as follows.

\[
x_i = f(N_i, E_i) = \begin{cases}
0, & E_{i+1} < 0 \\
1, & 0 \leq E_{i+1} \leq MaxE_{i+1} \\
\frac{MaxE_{i+1}}{E_{i+1}} - \frac{W_i + \Delta E_i - N_i \times \Delta t}{W_{i+1}} \times MaxE_{i+1}, & E_{i+1} > MaxE_{i+1}
\end{cases}
\]

Where, \(x_i\) denotes hydropower coupling factor at \(t\) time interval; \(N_i\) is power generation output at \(t\) time interval; \(\Delta t\) presents number of hours at \(t\) time interval; \(MaxE_{i+1}\) refers to reservoir’s allowed maximum energy storage value at the end of \(t\) time interval; \(E_i\), \(E_{i+1}\) show reservoir’s actual energy storage value at the beginning and end of \(t\) time interval, respectively; \(\Delta E_i\) denotes the to-be-added reservoir’s energy storage value when the hydropower station doesn’t generate power at \(t\) time interval, associated with the reservoir’s intake water at the time interval.

For the coupling factor mentioned above, the hydropower station has a corresponding calculation value at each time interval. In order to judge the overall output match in the 96 time intervals of the spot market, the corresponding coupling notion is proposed. The hydropower station’s coupling at the spot market is calculated by the equation below:

\[
C = \prod_{i=0}^{96} x_i
\]

Where, \(C\) means coupling; other parameters meaning the same as above.

The reservoir’s energy storage value is an important indicator to characterize the reservoir’s adjustable storage water generation under a certain water level. The energy storage value is drawn by increment in ascending water level. The reservoir’s energy storage value calculation formula under a certain water level is as follows.
Where, $E$ is reservoir’s energy storage value corresponding to water level $Z_j$, $J$ represents calculation segments, generally more than 5; $j$ denotes calculation segment No. ($j = 1 - J$); $Z_j$ means reservoir’s upper limit water level at $j$ calculation segment, short for calculation water level, $m^3$; $E_j(Z_j)$ refers to storage energy value at $j$ calculation segment, $kW \cdot h$; $\Delta W_j$ means reservoir’s water quantity at $j$ calculation segment, $m^3$; $v_i$ is hydropower station’s average water consumption rate at $j$ calculation segment, $m^3 / kWh$; $Z_0$ is presents reservoir’s dead water level, $m$; $\Delta Z$ shows water level step at calculation segment, $m$.

To study the coupling of hydropower station’s power generation and runoff, the individual hydropower station’s scheduling optimization model is established by taking the minimum deviation of fulfillment of sales target, and the water quantity balance, coupling factor, output restriction and down flow restriction.

2.1 Target function

Based on the modeling thought above, and targeting the minimum deviation of fulfillment of sales target, the author has established the target function expression formula (4):

$$\text{Obj} = \text{Min}(A - \bar{A})$$

Where, $A$ refers to hydropower station’s daily power generation, $kW \cdot h$; and $\bar{A}$ means hydropower station’s daily sales target power generation, $kW \cdot h$. The daily power generation calculation formula is shown in formula (5):

$$A = \sum_{t=1}^{T} k Q H \Delta t$$

Where, $T$ refers to time interval number; $k$ means output coefficient; $Q$ denotes power generation flow at $t$ time interval, $m^3/s$; $H$ shows power generation water head, $m$; $\Delta t$ is number of hours at $t$ time interval, 0.25h.

2.2 Constraints

The constraints are listed in Table 1.

| Constraints                  | Formula | Variable interpretation |
|-----------------------------|---------|-------------------------|
| Water quantity balance      | $V_{r_1} = V_r + (q_t - Q_t - S_t) \Delta t$ | $V_r$, $V_{r_1}$ refer to reservoir’s water storage quantity at the begin and end of $t$ time interval, respectively; $q_t$, $Q_t$ and $S_t$ indicate intake flow, down flow and discarded water flow at $t$ time interval; $V_{r_{\text{min}}}$ and $V_{r_{\text{max}}}$ refer to the minimum and maximum reservoir storage in order. $Q_{r_{\text{min}}}$, $Q_{r_{\text{max}}}$ refer to reservoir’s minimum and maximum down flow, respectively. $N_{r_{\text{min}}}$ and $N_{r_{\text{max}}}$ are the minimum and maximum output, respectively. $Z_t$ refers to the water level at the end of each time interval, $Z_{r_{\text{min}}}$ and $Z_{r_{\text{max}}}$ are respectively the dead water level and normal storage water level. |
| Reservoir’s water storage quantity | $V_{r_{\text{min}}} \leq V_r \leq V_{r_{\text{max}}}$ | |
| Reservoir’s down flow        | $Q_{r_{\text{min}}} \leq Q_r \leq Q_{r_{\text{max}}}$ | |
| Hydropower station output    | $N_{r_{\text{min}}} \leq N_r \leq N_{r_{\text{max}}}$ | |
| Water level restriction      | $Z_{r_{\text{min}}} \leq Z_r \leq Z_{r_{\text{max}}}$ | |
| Coupling factor              | $x_i = 1$ | |
3. Model Solution
The particle swarm algorithm (PSO) is the intelligent bionic algorithm based on bird predation [7]. Its core thought is derived from the theory of artificial life and evolution calculation. PSO starts from a set of random solution. Each particle in the particle swarm has two variables of position and speed. Each particle position is a viable solution. The target function of particle position coordinate is used to measure each particle superiority. By two variables of position and speed, the particle tracks the individual extreme value and global extreme value to keep updating position and seeking the optimal solution [8]. The particle cluster algorithm can get better application effect with respect to reservoir scheduling optimization. Therefore, PSO is used herein as the model solution algorithm. The specific algorithm flow is given in Figure 1.

4. Example Analysis
The study takes the Dagangshan hydropower station in Sichuan Dadu River area as an example. For the spot market, one day contains 96 time intervals of 15 min. Dagangshan hydropower station's daily sales objective power generation is set as 46,800,000 kWh. To compare the model optimization effect, one comparison scheme should be established as the Dagangshan hydro power station power generation process under the peak-plain-valley curve. Dagangshan hydropower station's basic parameter is shown in Table 2.

Table 2 Basic parameters of Dagangshan hydropower station
| Hydropower station | Maximum output/10,000 kW | Dead water level/m | Normal storage water level/m | Output coefficient k | Maximum down flow/m³ | Minimum down flow/m³ |
|--------------------|-------------------------|--------------------|-------------------------------|----------------------|----------------------|----------------------|
| Dagangshan         | 260                     | 1120               | 1130                          | 8.5                  | 7900                 | 165.4                |

PSO algorithm is used for scheduling optimization model solution. The water level curve contrast calculated by two schemes at the end of time interval is given in Figure 2.

In Figure 2, Dagangshan’s initial water level is 1127.80 m. After scheduling optimization calculation, the water level at the end of the last interval is also 1127.80 m. It means that the water level doesn’t subside during optimization. Power generation fully relies on intake flow so that the deviation between daily power generation and sales objective power generation is minimum. The final water level curve of the reservoir calculated from the peak-plain-valley is consistent with the curve calculated from the optimization calculation. The general trend rises before falling. Therefore, in order to achieve the daily sales target power generation, take in water first to increase water level. Increase the reservoir’s storage energy value, and then make the water level subside to acquire more power generation. The final water level in the final time interval of the comparison scheme doesn’t get back to the initial water level.
1127.80 m, but it is 1127.44 m. During the whole power generation of peak-plain-valley load distribution curve, the water level decreases by 0.36 m. Compared with the optimization calculation result, the water level doesn’t drop during optimization when the water intake flow process is fully consistent. It means that the water energy availability in the comparison scheme is smaller than the availability of the optimization model.

Figure 2 Water level curve comparison at the end of time interval

To analyze the superiority of two schemes more vividly, the author separately draws the power generation flow and outtake flow in both schemes, as shown in Figure 3 and Figure 4. In Figure 2 and 3, during optimization calculation, the final water level in a period of time in Dagangshan hydropower station varies within the restriction water level, and doesn’t reach the highest water level. The power generation flow at each time interval doesn’t equal the outtake flow. It means that there is no water discarded during optimization. In Figure 2 and 4, during the power generation of peak-plain-valley load distribution curve, the final water level in a period of time in Dagangshan hydropower station already reached the highest level at 8:00. It lasts 75 min. In these five time intervals, the outtake flow of Dagangshan hydropower station is larger than the power generation flow. It means that all these five time intervals produce discarded water, and the model mentioned herein shows a better optimization effect.

Table 3 Target function calculation result comparison

| Scheme                        | Daily power generation/kWh | Daily sales objective power generation/kWh | Deviation of fulfillment of sales objective | Coupling |
|-------------------------------|-----------------------------|--------------------------------------------|--------------------------------------------|----------|
| Scheduling optimization model | 46789982                    | 46800000                                   | 0.02%                                      | 1        |
| Peak-plain-valley curve       | 46786110                    | 46800000                                   | 0.03%                                      | 96%      |
According to data analysis and comparison in Table 3, when the daily sales objective power generation is same, the daily power generation of scheduling optimization model is 46,789,982 kWh, 3,872 kWh more than the daily power generation 46,786,110 kWh drawn from the peak-plain-valley load distribution curve. The deviation of fulfillment of sales objective under the scheduling optimization model is 0.02%, 0.01% smaller than 0.03% deviation of fulfillment of sales objective drawn from the peak-plain-valley load distribution curve. It means that the scheduling optimization model herein can effectively increase Dagangshan hydropower station's power generation capacity and reduce sales objective deviation so that the daily power generation is closer to the daily sales objective power generation. The coupling of scheduling optimization model and peak-plain-valley load distribution curve is more than 0. It means that the storage power generation at each time interval of Dagangshan hydropower station under both schemes are more than power generation output. Besides, the hydropower and output match for the Dagangshan hydropower station under both schemes. However, the coupling of peak-plain-valley load distribution curve is 96%, smaller than one, the coupling for scheduling optimization model. The reason is that five time intervals produce discarded water during power generation under the peak-plain-valley load distribution curve. During the power generation of scheduling optimization model, there is no discarded water. Therefore, the former's coupling is slightly lower than the latter's. The more the coupling, the less the discarded water.

5. Conclusion
Starting from the hydropower station’s hydropower output match in time sequence, the author put forward the hydropower coupling factor and coupling. By taking it as a restriction condition, the hydropower station scheduling optimization model based on hydropower coupling was established. PSO was used herein as the model solution algorithm. The model effectiveness was validated by the example of Dagangshan hydropower station in Dadu River area. Conclusions below are drawn through analysis:

1) Under the condition of same daily sales objective power generation and intake water flow process, the original water level and the final water level in a day are consistent under the scheduling optimization model. No discarded water is produced during power generation and the water level doesn’t subside. Under the peak-plain-valley load distribution curve, the final water level is lower than the original water level. The water level decreases somewhat and the power generation process produces discarded water. It means that the optimization model can enhance water energy availability and reduce discarded water.

2) Under the scheduling optimization model, the daily power generating capacity is more than that under the peak-plain-valley curve. The error of fulfillment of sales objective under the scheduling optimization model is smaller than that under the peak-plain-valley curve. It means that the scheduling optimization model can effective improve the hydropower station’s power generation capacity so that the daily power generation is closer to the daily marketing target of power generation, thus reducing the deviation of the marketing target.

However, this paper still has deficiencies, such as failing to consider the coupling of electricity price, hydropower and electric power. How to establish the coupling scheduling optimization model of electricity price, hydropower and electric power will be the research focus in the next phase.

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