Research Article

Long-Term Optimal Dispatching of Hydropower Station Based on Controlling the Frequency of Reservoir Level Fluctuation

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Received 26 March 2022; Revised 14 May 2022; Accepted 27 May 2022; Published 20 June 2022

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In this paper, a method for long-term optimal operation of hydropower station is proposed to control the frequency of reservoir level fluctuation. We introduce the integer variable which describes the rise and fall of the reservoir level, the number of changes, and the state transition equation for the change of the reservoir level fluctuation into the dynamic programming method. This method can obtain the global optimal solution under the control of different numbers of reservoir level rise and fall, thus improving the controllability and practicability of optimal operating results. We consider the maximum number of water level fluctuations as a constraint condition while the reservoir level, the state of fluctuation, and the number of state changes that have occurred as the three state variables to construct a dynamic programming model. Three state transition equations are the water balance, the state of the reservoir level rise and fall, and the number of fluctuations. Besides, the penalty function is used to handle minimum output and surplus water. We solve this model by using a dynamic programming reverse recursion equation. The application of this method in the Manwan Hydropower Station shows that it can effectively solve the frequent water level fluctuation problem that is generally inconsistent with the actual situation in the long-term optimal dispatch scheme of hydropower stations and improve the practicability of the optimal dispatch results.

1. Introduction

Hydropower is large-scale renewable energy with complete development technology in China and even in the world [1]. The optimal operation of the hydropower station plays an important role in improving the operational efficiency of the hydropower station [2]. The solution of the hydropower station optimal operation model belongs to the constrained nonlinear programming problem. Many solving methods have been explored all over the world, including traditional algorithms such as linear programming [3], nonlinear programming [4], progressive optimization algorithm (POA) [5], dynamic programming (DP) [6], and intelligent evolutionary algorithms, such as genetic algorithm [7], particle swarm optimization [8], ant colony optimization [9], and the combination algorithm of the above methods [10–12].

DP is one of the most suitable and classical mathematical methods for solving the optimization problem of the multistage decision-making process [13]. DP is widely used to deal with water resource planning and management problems as it can describe the stochastic characteristics and nonlinear relations and is not affected by the convexity and continuity of the objective function [14]. However, when the number of power stations increases, the number of states increases exponentially, resulting in an exponential increase in computing time and required storage capacity. This is the “curse of dimensionality” that limits the application of DP. Scholars have done a lot of in-depth research and put forward many improved DP algorithms to alleviate the dimension disaster such as incremental dynamic programming (IDP) [15,16], discrete differential dynamic programming (DDDP) [17,18] which can be regarded as the general form of IDP, dynamic programming successive...
approximations (DPSA) [19,20] based on the idea to decompose a multidimensional problem into multiple one-dimensional problems, and some hybrid methods of these algorithms [21–23]. These improved DP-based algorithms do have higher efficiency and do increase the benefits of hydropower generation.

However, compared to most researchers who concentrate on finding the best optimization algorithm, the decision-makers look into operational strategies that are more practical to be used [24]. Some recent research also shows that decision-makers are more willing to use simulation models which can better describe the real process than optimization [25, 26]. At present, the commonly used dynamic programming methods for optimal operation of hydropower stations mainly focus on maximizing the benefits of hydropower generation, and its results are often inconsistent with the actual operation habits, especially it will make the water level of reservoirs fluctuate frequently. Water level fluctuation may influence the soil degradation, sediment process, water quality, and the downstream ecosystem [27–29]. Affecting by these factors, the reservoir usually has only a limited number of storage and release processes in a year in the actual operation. This apparent inconsistency between practice communities and research can be solved by directly incorporating the needs of practitioners into the research field [30]. According to the authors’ knowledge, few studies have considered this water level fluctuation problem that is not allowed in the real operation process while improving algorithm efficiency and power generation. Therefore, it is necessary to put forward a novel method to solve the problem of frequent rise and fall of reservoir level which is generally existed in the long-term optimal operation scheme of hydropower stations to improve the practicality of the optimization method.

In this study, a novel long-term optimal operation method for controlling the frequency of reservoir level fluctuation is proposed. Compared with the traditional DP method, this method introduces a new state variable into the traditional DP method. Therefore, this method can obtain the global optimal solution under the control of different rise and fall times.

2. Multistate Optimization Model for Water Level Fluctuation

The long-term optimal operation of hydropower stations usually takes a year as the operation period and a month as the calculation period. Under the conditions of the given inflow process and reservoir level, considering the actual operation constraints, the reservoir level, and the output process are optimized. The maximum generation model is often used as the objective function. This paper proposes the restriction of the number of rise and fall of the reservoir level, controls the number of rise and fall of the reservoir level, and obtains the global optimal solution under the control of the different rise and fall times.

2.1. Objective Function.

$$
\max E = \sum_{t=1}^{T} \rho^t \Delta^t,
$$

where $E$ is the objective function of power generation, $T$ is the final period, $\rho^t$ is the output of the power station during $t$ period, and $\Delta^t$ is the number of hours during $t$ period.

2.2. Constraints. The equation of water balance is as follows:

$$
S^{t+1} = S^t + (\ln^t - Q^t - w^t)\Delta^t,
$$

where $S^t$ is the water storage capacity of the hydropower station at the beginning of period $t$, $S^{t+1}$ is the initial water storage capacity of the hydropower station at the period $t + 1$, $\ln^t$ is the inflow of the hydropower station in the period $t$, $Q^t$ is power generation flow in period $t$, and $w^t$ is surplus water flow in period $t$.

Initial and final water level constraints are as follows:

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Hydropower output constraints are as follows: 
\[ P_t \leq p_t^i \leq \bar{P}_t, \]  
(6)

where \( z_s \), \( z_e \) are the initial and final water level requirements of the power station dispatching period; \( Q^t \) is the Outbound flow during period \( t \), \( Q^t = q^t + w^t \); \( Q^0 \), \( Q^T \) are the lower and upper limits of reservoir discharge; \( z^0_t \), \( z^\prime_t \), \( z^\prime\prime_t \) are the initial water level in period \( t \), and the lower and upper limits of the initial water level; \( p^i_t \), \( \bar{P}_t \) are the lower and upper limits for hydropower station output.

Restriction on the number of times of rise and fall of reservoir level is as follows:
\[ \sum_{i=1}^{T} \mu^t_i \leq N, \]  
(7)

where \( \mu^t_i \) indicates whether the rise and fall of the reservoir level at the beginning and end of period \( t \) has changed from the previous period. If it has changed \( \mu^t_i = 1 \), otherwise \( \mu^t_i = 0 \); \( N \) indicates the maximum number of allowable changes in the water level of the reservoir.

Figure 1 takes \( N = 2 \) as an example, \( z \) is the reservoir level status, \( z_0 < z_1 < z_2 \); \( \gamma \) indicates whether the reservoir level is rising and falling, \( \gamma = 0 \) means the reservoir level is rising, \( \gamma = 1 \) means the reservoir level is falling; \( \eta \) is the number of times that the reservoir level rises and falls before period \( t \).

3. Calculation Framework for the Optimization Model

The integer variable describing the rise and fall of the reservoir level and the number of changes and the state transition equation of the state change of the reservoir level rise and fall are introduced into the dynamic programming method of the reservoir level as a state variable. Take the maximum number of changes in the lifting state as a constraint condition to construct a dynamic programming model with frequency control of reservoir level changes. Consider the reservoir level, the state of rise and fall, and the number of state changes that have occurred as the three state variables. The three-state transition equations are the water balance, the state of the reservoir level rise and fall, and the number of rises and falls. The penalty function is used to handle minimum output and surplus water. The model is solved by using a dynamic programming reverse recursion equation. Steps 1 to 17 are the total calculation procedure of the multistate DP and have been arranged in the order of calculation. The steps are as follows.

Step 1. Reading the data of the hydropower station. The reservoir level in period \( t \) is evenly dispersed between the maximum and minimum values, and \( M_i \) discrete points of water level are obtained. \( z^i_t \) is the water level of the \( i \) discrete point at the beginning of period \( t \), \( t = 1 \sim T + 1 \), and \( T \) is the number of scheduling periods. \( t = 1 \) means that there is only one discrete water level in the initial stage of dispatching, that is, the initial water level, \( M_1 = 1 \). \( t = T + 1 \) means that there is only one discrete water level at the end of the dispatching termination period, that is, the final water level, \( M_{T+1} = 1 \). \( M_i \) for other periods is set according to the calculation accuracy.

Step 2. Detailed definition of water level fluctuation state variables and state transition decision functions. It is defined that the water level changes from falling to rising, or from rising to falling to be a water level fluctuation. The maximum fluctuation times of reservoir level in the operation period is set as \( N \). Define the rising and falling state of the water level under the water level \( z^i_t \) during the period \( t \) as \( \gamma^t_i \), \( \gamma^t_i = 0 \) indicates that \( z^i_t \) is in the rising stage, and \( \gamma^t_i = 1 \) indicates that \( z^i_t \) is in the falling stage. Define the number of fluctuations that have occurred when the water level reaches \( z^i_t \) during the period \( t \) as \( \eta^t_i \), \( \eta^t_i \leq N \). Set the benefit function in the state \((z^i_t, \gamma^t_i, \eta^t_i)\) as \( F_t(z^i_t, \gamma^t_i, \eta^t_i) \), which is the optimal benefit from period \( t \) to the end of the scheduling period in the state \((z^i_t, \gamma^t_i, \eta^t_i)\). The decision function is \( Z_t(z^i_t, \gamma^t_i, \eta^t_i) \), \( G_t(z^i_t, \gamma^t_i, \eta^t_i) \), and \( H_t(z^i_t, \gamma^t_i, \eta^t_i) \), which, respectively, represent the discrete position label of the final water level decision, the decision of the output rise and fall state, and the decision of the number of rise and fall state changes that have occurred.

Step 3. Set time period \( t = T \).

Step 4. Set the discrete point of water level as \( z^i_t, i = 1 \).

Step 5. Set the water level rising and falling state as \( \gamma^t_i = 0 \).

Step 6. Set the fluctuation frequency of water level as \( \eta^t_i = 0 \).

Step 7. Set the discrete position of water level at the end of the time period as \( j = 1 \).

Step 8. Calculating the objective function for hydropower generation. Fixed initial water level \( z^1_t \) and final water level \( z^{T+1}_t \) for constant water level regulation calculation, the average output \( p^1_{i,j} \) power generation flow \( q^t_{i,j} \) and water abandonment flow \( w^t_{i,j} \) are obtained. If \( p^1_{i,j} \) is a negative value for the outgoing flow under the condition of a fixed water level, it means that the water balance constraint cannot be satisfied:
\[ f^t_{i,j} = p^1_{i,j} \Delta^t + g1(q^t_{i,j}) + g2(p^1_{i,j}) + g3(w^t_{i,j}). \]  
(8)

\[ g1(p^1_{i,j}) = \begin{cases} 
\text{ap}_{i,j}^t, & p^1_{i,j} < 0, \\
0, & p^1_{i,j} \geq 0.
\end{cases} \]

\[ g2(p^1_{i,j}) = \begin{cases} 
-\text{u}_{i,j}^t (\bar{P}_i - p^1_{i,j})^2, & p^1_{i,j} < \bar{P}_i, \\
0, & p^1_{i,j} \geq \bar{P}_i.
\end{cases} \]  
(9)

\[ g3(w^t_{i,j}) = \begin{cases} 
-\text{cw}_{i,j}^t, & w^t_{i,j} > 0, \\
0, & w^t_{i,j} = 0.
\end{cases} \]
Equation (8) is used to calculate the objective function where $g_1(p_{fg}^i)$, $g_2(p_{fg}^i)$, and $g_3(w_{fg}^i)$ are the penalties for water balance, minimum output, and surplus water, respectively. $a$, $b$, and $c$ are penalty coefficients, where $a$ is approximate infinity and $b$ and $c$ can be set flexible according to the characteristics of the problem to be solved.

Step 9. Updating the decision functions according to the state variables.

If $y_i^t = 0$, $z_i^t \leq z_i^{t+1}$, and $f_{i,j}^t + F_{t+1}(z_j^{t+1}, 0, \eta_j^t) > F_t(z_i^t, 0, \eta_i^t)$, then update $F_t(z_i^t, 0, \eta_i^t) = f_{i,j}^t + F_{t+1}(z_j^{t+1}, 0, \eta_j^t)$, $Z_t(z_i^t, 0, \eta_i^t) = j$, $G_t(z_i^t, 0, \eta_i^t) = 0$ and $H_t(z_i^t, 0, \eta_i^t) = \eta_i^t$.

If $y_i^t = 0$, $z_i^t > z_i^{t+1}$, $\eta_i^t + 1 \leq N_t$, and $f_{i,j}^t + F_{t+1}(z_j^{t+1}, 1, \eta_j^t) > F_t(z_i^t, 0, \eta_i^t)$, then update $F_t(z_i^t, 0, \eta_i^t) = f_{i,j}^t + F_{t+1}(z_j^{t+1}, 1, \eta_j^t)$, $Z_t(z_i^t, 1, \eta_i^t) = j$, $G_t(z_i^t, 1, \eta_i^t) = 1$, and $H_t(z_i^t, 0, \eta_i^t) = \eta_i^t + 1$.

If $y_i^t = 1$, $z_i^t \geq z_i^{t+1}$, and $f_{i,j}^t + F_{t+1}(z_j^{t+1}, 1, \eta_j^t) > F_t(z_i^t, 1, \eta_i^t)$, then update $F_t(z_i^t, 1, \eta_i^t) = f_{i,j}^t + F_{t+1}(z_j^{t+1}, 1, \eta_j^t)$, $Z_t(z_i^t, 1, \eta_i^t) = j$, and $H_t(z_i^t, 0, \eta_i^t) = \eta_i^t$.

If $y_i^t = 1$, $z_i^t < z_i^{t+1}$, $\eta_i^t + 1 \leq N_t$, and $f_{i,j}^t + F_{t+1}(z_j^{t+1}, 0, \eta_j^t) > F_t(z_i^t, 1, \eta_i^t)$, then update $F_t(z_i^t, 1, \eta_i^t) = f_{i,j}^t + F_{t+1}(z_j^{t+1}, 0, \eta_j^t)$, $Z_t(z_i^t, 1, \eta_i^t) = j$, $G_t(z_i^t, 1, \eta_i^t) = 0$, and $H_t(z_i^t, 0, \eta_i^t) = \eta_i^t + 1$.

Step 10. Set $j = j + 1$, if $j \leq M_{t+1}$, return to Step 8. Otherwise, go to Step 11.

Step 11. Set $\eta_i^t = \eta_i^t + 1$, if $\eta_i^t \leq N_t$, return to Step 7. Otherwise, go to Step 12.

Step 12. If $y_i^t = 0$, set $y_i^t = 1$, return to Step 6. Otherwise, go to Step 13.

Step 13. Set $i = i + 1$, if $i \leq M_t$, return to Step 5. Otherwise, go to Step 14.

Step 14. Set $t = t - 1$, if $t \geq 1$, return to Step 4. Otherwise, go to Step 15.

Step 15. Set the current period as $t = 1$ and look for the maximum decision of $F_t(z_i^t, y_i^t, \eta_i^t)$ in the combination of $i = 1 \sim M_t$, $y_i^t = 0$ or 1, $\eta_i^t = 1 \sim N$, denoted as $Z_{t}^\ast$, $G_{t}^\ast$, and $H_{t}^\ast$; fix the water level from the initial to $z_{t_{i=1}}^\ast$ for calculation.

Step 16. Set $t = t + 1$, if $t \leq T$, obtain the optimal decisions $Z_t^\ast = Z_t(z_{t_i}^\ast, y_{t_i}^\ast, \eta_{t_i}^\ast)$, $G_t^\ast = G_t(z_{t_i}^\ast, y_{t_i}^\ast, \eta_{t_i}^\ast)$, and $H_t^\ast = H_t(z_{t_i}^\ast, y_{t_i}^\ast, \eta_{t_i}^\ast)$ during period $t$; fix the water.

Step 17. Count the dispatch calculation indicators and obtain the hydropower station dispatch plan.

4. Case Study

Manwan Hydropower Station in Yunnan Province is taken as the case study. Manwan Hydropower Station is a seasonal regulation hydropower station with an installed capacity of 1,550 MW. Figure 2 shows the schematic diagram of cascade hydropower stations in Lancang River Basin and the specific location of Manwan hydropower station.

Due to the poor regulation capacity, the reservoir level changes very frequently according to the traditional maximum power generation results. On the one hand, when the reservoir level is low, it is necessary to increase the power generation head by storing water under the condition of meeting the constraint of minimum discharge or minimum output. On the other hand, when the incoming water is large in the later period, it is necessary to increase the output and reduce the reservoir level to avoid the generation of surplus water. Due to the relatively small storage capacity, Manwan reservoir can complete the process from full storage to empty, or from empty to full storage within 1–2 months. However, in the formulation of a long-term power generation plan, the over-frequent reservoir level storage and discharge are of little significance, because the implementation of the actual dispatching plan also needs to take into account the medium-short time scale meteorological forecast and power grid load variation factors which are difficult to be considered in the formulation of the long-term plan. In practice, the long-term dispatching plan only considers the trend of water level variation in several periods, such as before, during, and after flood season, and does not consider the change of water level in a short period to raise water head or avoid the generation of surplus water. However, the results obtained by the traditional maximum generation model often do not meet the actual requirements, and it is necessary to manually adjust the optimization results. This problem is common in the operation of seasonal
adjustment and incomplete annual adjustment reservoirs in China.

In the following, the method proposed in this paper is used to reflect the requirements of dispatchers on the frequency of reservoir level changes in the optimization calculation by solving the optimal dispatch plan of the Manwan Hydropower Station in a certain year and then analyze the results. There are 12 periods, and the duration of each period is one month. Figures 3–9 show the optimal scheduling scheme that limits the change times of reservoir level rise and fall from 1 to 7 times.

The result in Figure 9 is the result without limiting the number of changes in the state of water level in the reservoir, and the state of water level changes 7 times. Moreover, it is also the calculation result of the conventional dynamic programming without limiting the number of changes in the state of water level. The scheme of 1–6 times of fluctuation of reservoir level considers the practicability of long-term electricity quantity of the hydropower system and operation scheme of hydropower station. Figure 3 to Figure 8 are the results of the scheduling process which limits the number of water levels rise and fall. Compared with the power generation process of the conventional DP optimal scheduling (Figure 9), it can be seen that the scheduling scheme formulated by the algorithm in this paper can play a flexible role in limiting the water level fluctuation of the hydropower system. Besides, this method can provide comprehensive operation plans for decision-makers under different water level fluctuation scenarios which is more flexible and practical than the traditional DP algorithm.

Table 1 shows the total power generation under different times of change in reservoir level fluctuation state. Hydropower generation is directly influenced by water level fluctuation. Each time the water level fluctuation, the reservoir completes a procedure of water storage and water release. The more the water level change, the more
Figure 5: Reservoir level optimization results with the water level fluctuation state of Manwan Hydropower Station changing at most 3 times.

Figure 6: Reservoir level optimization results with the water level fluctuation state of Manwan Hydropower Station changing at most 4 times.

Figure 7: Reservoir level optimization results with the water level fluctuation state of Manwan Hydropower Station changing at most 5 times.
Hydropower is produced. The times of water level change and the total power generation approximate a linear relationship, and each time the water level changes, the power generation increased to near 0.3% at the same time. We noticed that the power generation of 3 times of change is lower than the power generation of 2 times of change which is caused by the accuracy of the calculation. However, the overall result satisfies the increasing trend.

Table 2 and Table 3 show the dispatching situation of 7 times and 1-time change of reservoir water level and the power generation of each dispatching period. It can be seen that by reducing the fluctuation frequency of water level, the maximum reduction ratio of electricity generation is 1.8%, and the main period of electricity reduction in flood season. Due to the variable inflow of flood season, flood resources are usually difficult to fully utilize, and the benefits obtained by optimal dispatching are generally difficult to fully realize. Therefore, it is more realistic to ignore the increase in electricity caused by frequent water level fluctuations in long-term dispatch. Dispatchers can choose the actual plan according to the scheduling habits and actual conditions in the results of the number of changes in different water levels.
up and down states. This provides an effective and practical technical means to solve the problem of frequent rise and fall of reservoir level which is not consistent with the actual situation in the long-term optimal operation scheme of hydropower station.

5. Conclusion

In this paper, a long-term optimal dispatching model of hydropower station based on controlling the frequency of reservoir level fluctuation is proposed and solved by using a multistate DP. Compared with the existing approaches, the long-term optimal dispatching method proposed in this paper can effectively solve the frequent rise and fall of the reservoir level that is common in the long-term optimal dispatching scheme of hydropower stations which does not match the actual situation of operation. By directly incorporating the needs of practitioners into the mathematical modeling, decision-makers can choose the actual plan based on dispatch habits and actual conditions in the results of different reservoir level fluctuations which significantly improve the flexibility and practicality of the results.

Data Availability

Some data, models, or code generated or used during the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The research work described in this paper was supported by the National Natural Science Foundation of China (52179005).

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