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Short-term power generation scheduling rules for cascade hydropower stations based on hybrid algorithm

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Abstract: Power generation dispatching is a large complex system problem with multi-dimensional and nonlinear characteristics. A mathematical model was established based on the principle of reservoir operation. A large quantity of optimal scheduling processes were obtained by calculating the daily runoff process within three typical years, and a large number of simulated daily runoff processes were obtained using the progressive optimality algorithm (POA) in combination with the genetic algorithm (GA). After analyzing the optimal scheduling processes, the corresponding scheduling rules were determined, and the practical formulas were obtained. These rules can make full use of the rolling runoff forecast and carry out the rolling scheduling. Compared with the optimized results, the maximum relative difference of the annual power generation obtained by the scheduling rules is no more than 1%. The effectiveness and practical applicability of the scheduling rules are demonstrated by a case study. This study provides a new perspective for formulating the rules of power generation dispatching.

Key words: *scheduling rule; short-time power generation dispatching; hybrid algorithm; cascade hydropower station*

1 Introduction

Two conventional approaches can be used to obtain the optimal scheduling of power generation in cascade hydropower stations. One is the reservoir operation chart (Yang et al. 2010; Yu et al. 2010; Chen et al. 2007). However, the latest results of runoff prediction cannot be used with this method, and the scheduling results are too conservative to represent the advantages and economic benefits of scheduling of cascade hydropower stations. Alternatively, a basic scheduling process can be obtained using a variety of traditional algorithms or intelligent algorithms based on the long-term data series of runoff. Yoo (2009) applied a linear programming method to maximize hydropower energy generation. Pérez-Díaz et al. (2010) proposed nonlinear programming based on a scheduling model for solving short-term

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operation scheduling of a hydropower plant. Li et al. (2009) used the immune algorithm-based particle swarm optimization (PSO) for optimized load distribution among cascade hydropower stations. Similar studies have been reported by Mandal and Chakraborty (2011) for solving combined economic emission scheduling of hydrothermal systems with cascade reservoirs using the PSO algorithm, and by Hota et al. (2009) for solving short-term optimal hydrothermal scheduling using an improved PSO technique. Lakshminarasimman and Subramanian (2008) developed a modified hybrid differential evolution algorithm for short-term scheduling of hydrothermal power systems with cascade reservoirs. Yuan and Yuan (2006) proposed a new cultural algorithm to solve the optimal daily generation scheduling of hydrothermal power systems. Liang (1999) applied grey relation analysis to hydroelectric generation scheduling. Huang (1998) applied the genetic-embedded fuzzy system approach to hydroelectric generation scheduling. Liang and Hsu (1995) developed a hybrid artificial neural network-differential dynamic programming approach for short-term hydroelectric scheduling.

It is observed from the above literature review that although many studies have provided the basic rules of reservoir operation, only some general conclusions have been obtained, there have been very few studies on the clearly different scheduling rules for the different varieties of runoff, and the feasibility of the methods is relatively poor. In order to improve the short-term power generation scheduling rules of cascade hydropower stations on the Jinsha River, studies on the practical and effective scheduling rules were carried out using the progressive optimality algorithm (POA) in combination with the genetic algorithm (GA).

2 Mathematical model

In this study, the maximum power output during the scheduling period was regarded as the objective. Thus the objective function can be expressed as follows:

$$E = \max\left(\sum_{i=1}^{G}\sum_{t=1}^{T} P_{i,t}\Delta t\right) = \max\left(\sum_{i=1}^{G}\sum_{t=1}^{T} K_i Q_{i,t} H_{i,t}\Delta t\right) \tag{1}$$

where E is the total generated energy, G is the number of cascade hydropower stations, T is the number of time intervals (Δt), $P_{i,t}$ is the average output of the ith hydropower station in the tth time interval, K_i is the output coefficient of the ith hydropower station, $Q_{i,t}$ is the power flow of the ith hydropower station in the tth time interval, and $H_{i,t}$ is the water head of the ith hydropower station in the tth time interval.

The objective function is subjected to the following constraints:

(1) Water balance equations:

$$\begin{cases} V_{i,t+1} = V_{i,t} + \left(I_{i,t} - Q'_{i,t} - S_{i,t}\right)\Delta t \\ I_{i,t} = Q'_{i-1,t-\tau_j} + q'_{i,t} \end{cases} \qquad \left(i = 1,\ 2,\cdots,\ G;\ t = 1,\ 2,\cdots,\ T\right) \tag{2}$$

where $V_{i,t}$ and $V_{i,t+1}$ are, respectively, the storage capacity of the ith hydropower station in the tth and (t+1)th time intervals; $I_{i,t}$ and $Q'_{i,t}$ are the reservoir inflow and outflow of the ith hydropower station in the tth time interval, respectively; $S_{i,t}$ and $q'_{i,t}$ are the surplus flow and region inflow of the ith hydropower station in the tth time interval, respectively; and τ_i is the water flow's travel time between the (i-1)th and ith hydropower stations.

(2) Storage capacity constraint:

$$V_{i\min} \le V_{i,t} \le V_{i\max} \quad \left(i=1,\ 2,\cdots,\ G;\ t=1,\ 2,\cdots,\ T\right) \tag{3}$$

where $V_{i\min}$ is the dead storage of the ith hydropower station, and $V_{i\max}$ is the storage corresponding to the normal water level of the ith hydropower station. During the flood season, $V_{i\max}$ is the storage corresponding to the limiting water level.

(3) Power constraint:

$$N_{i\min} \le N_{i,t} \le N_{i\max} \quad \left(i=1,\ 2,\cdots,\ G;\ t=1,\ 2,\cdots,\ T\right) \tag{4}$$

where $N_{i,t}$ is the actual output of the ith hydropower station in the tth time interval, and $N_{i\min}$ and $N_{i\max}$ are the highest and lowest outputs of the ith hydropower station, respectively.

(4) Discharge constraint:

$$Q_{i\min} \le Q_{i,t} \le Q_{i\max} \quad \left(i=1,\ 2,\cdots,\ G;\ t=1,\ 2,\cdots,\ T\right) \tag{5}$$

where $Q_{i\min}$ is the minimum ecological flow of the ith hydropower station determined by the water resources department, and $Q_{i\max}$ is the permitted maximum discharge flow of the ith hydropower station to guarantee the flood control security of downstream region.

3 Hybrid algorithm and computational process

The hybrid algorithm adopts GA in the inner loop and POA in the outer loop, integrating the advantages of traditional algorithms and intelligent algorithms. GAs were proposed by Holland (1975) as an abstraction of biological evolution, drawing on ideas from natural evolution and genetics for the design and implementation of robust adaptive systems. GAs have been used to optimize the reservoir operation because of their potential as optimization techniques for complex functions (Goldberg 1989; Romero and Carter 2001). Studies of POA for reservoir operation were reported by Nanda et al. (1986) and Xuan et al. (2009). The calculation steps of the hybrid algorithm are as follows:

Step 1: The initial water level trajectory of each hydropower station is determined. It can be the dead water level or the normal water level. $z_{i,0},\ z_{i,1},\ z_{i,2},\cdots,\ z_{i,T}$ is defined as the initial water level trajectory of the ith hydropower station, where $z_{i,j}\left(i=1,\ 2,\cdots,G;\ j=1,\ 2,\cdots,T\right)$ is the water level of the ith hydropower station at time point j.

Step 2: The optimal output process of each hydropower station is sought from upstream to downstream. Considering the ith ($1 \le i \le G$) hydropower station as an instance, the water level $z_{i,0}$ at time point zero and $z_{i,2}$ at time point 2 must be fixed, and then the water level $z_{i,1}$ at time point 1 can be adjusted using GA to get the maximum generated energy during the zero time interval and 1st time interval. Thus, after optimizing, the water level trajectory of the ith hydropower station is changed to $z_{i,0},\ z'_{i,1},\ z_{i,2},\cdots,\ z_{i,T}$ ($1 \le i \le G$).

Step 3: Similarly, the water level in next time point is adjusted. The water level $z'_{i,1}$ at time point 1 and $z_{i,3}$ at time point 3 must be fixed, and then the water level $z_{i,2}$ at time point 2 can be adjusted using GA to get the maximum generated energy during the 1st time interval and the 2nd time interval. Thus, after optimizing, the water level trajectory of the *i*th hydropower station is changed to $z_{i,0},\ z'_{i,1},\ z'_{i,2},\cdots,\ z_{i,T}$ $(1\le i\le G)$.

Step 4: Step 3 is repeated until the iteration times reach the number of time intervals (T). Based on initial conditions and the constraint conditions of the cascade hydropower station, the stage hydrograph, output process, outflow process, and the total output of this cascade hydropower station can be obtained.

Step 5: The water level trajectory is initialized again using the latest stage hydrograph, and then the process returns to step 2.

Step 6: If the convergence condition that the difference in total output of the cascade hydropower station between adjacent iterations reaches the specified precision is met, the process is over. Otherwise, it returns to step 5. The flow chart of the hybrid algorithm is presented in Fig. 1.

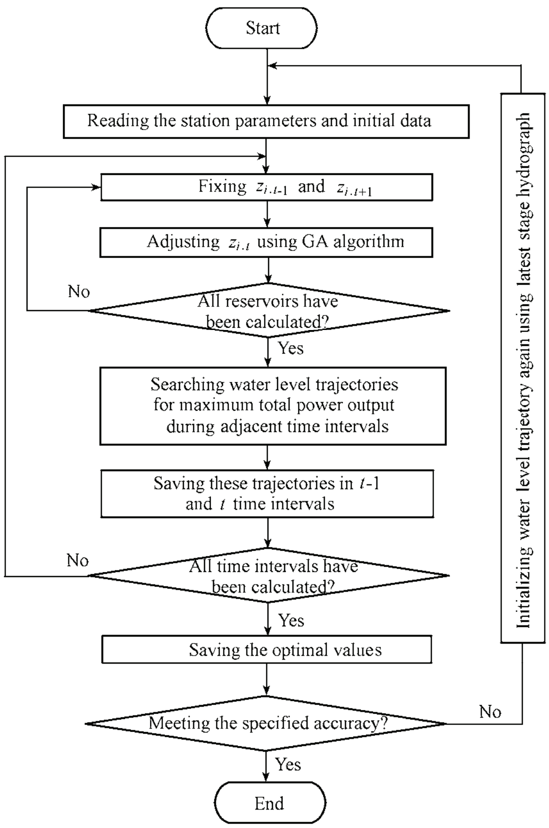

Fig. 1 Flow chart of hybrid algorithm

4 Scheduling rules for cascade hydropower stations in Jinsha River

Taking six hydropower stations on the Jinsha River as examples, the steps for establishing the scheduling rules are as follows: First, based on the mathematical model, the daily runoff process in three typical years and large numbers of simulated daily runoff processes are analyzed using the hybrid algorithm to obtain the corresponding optimal scheduling processes. Second, these optimal results are summarized using the principles of statistics, and then the specific scheduling rules under different conditions of cascade hydropower stations are given. Finally, according to expert experience, those scheduling rules are formulated in the form of experience formulas which are very convenient for guiding the short-term power generation scheduling of cascade hydropower stations.

The Jinsha River is the upper reaches of the Yangtze River. The cascade hydropower station studied in this study is located on the middle reaches of the Jinsha River. It includes six hydropower stations: Liyuan, Ahai, Jinanqiao, Longkaikou, Ludila, and Guanyinyan hydropower stations from upstream to downstream. Characteristic parameters of six hydropower stations on the Jinsha River are listed in Table 1. The scheduling period of this cascade hydropower station is one year, and the length of time intervals is one day, so the number of time intervals is 364, and the space is relatively far between hydropower stations. Thus, τ_i did not need to be considered in this study.

Table 1 Characteristic parameters of six hydropower stations

Hydropower station (from upstream to downstream)	Installed capacity (MW)	Regulation capacity	Total storage capacity of reservoir (10^8 m³)	Regulation storage capacity (10^8 m³)	Normal water level (m)	Dead water level (m)	Limited water level (m)
Liyuan	2 400	Week	8.05	1.73	1 618	1 605	1 605.0
Ahai	2 000	Day	8.85	2.38	1 504	1 492	1 493.3
Jinanqiao	2 400	Week	9.13	3.46	1 418	1 398	1 409.9
Longkaikou	1 800	Day	5.58	1.13	1 298	1 290	1 290.0
Ludila	2 100	Week	17.18	3.76	1 223	1 216	1 216.0
Guanyinyan	3 000	Week	22.50	3.83	1 134	1 126	1 126.0

Note: The limited water levels are the data in July, and the limited water level at Guanyinyan Hydropower Station in August is 1 129 m.

4.1 Basic principle and normal operation for short-term power generation scheduling

4.1.1 Basic principle

Based on the power system load requirements, the water level of the reservoir which has weekly or daily regulation capacity should be maintained at the high water level as far as possible. In other words, the water level should be maintained at the normal water level during the non-flood season and at the limited water level during the flood season as far as possible. If the flood process is more than that needed for generating the expected output according to the short-term runoff forecast, part of the regulation storage capacity of the reservoir should be vacated early to store this flood. Nevertheless, the water level must be return to the high water level at the end of the flood process as soon as possible.

4.1.2 Normal operation

If the storage capacity of cascade reservoirs needs to be vacated early before the flood season, it should start from the upstream reservoirs and move to the downstream reservoirs. However, at the end of flood season, the water levels of these reservoirs must be return to the high water level in time, following a sequence from downstream to upstream.

4.2 Power generation scheduling rules of cascade hydropower stations

After analyzing the optimal results obtained by the hybrid algorithm, the power generation scheduling rules can be determined. To better guide the operation of hydropower stations, the scheduling period can be divided into a dry-flood transition period and general period. The length of the former is a variable, meaning that the values at different hydropower stations are different, and it will be further explained later. Naturally, the scheduling period, in addition to the dry-flood transition period, is defined as general period.

4.2.1 Rules during general period

The forecast period means the period of validity of runoff prediction. If the natural runoffs of these six stations are all less than those needed for generating the expected output during the forecast period according to the runoff prediction, the cascade hydropower stations should be in normal operation. However, if the natural runoff of any station is more than that needed for generating the expected output during the forecast period according to the runoff prediction, the six hydropower stations need joint pre-discharge scheduling.

When adopting joint pre-discharge scheduling, the termination time needs to be accurately determined. First, the final time for each station in which the natural runoff is more than that needed for generating the expected output during the forecast period is determined according to the runoff prediction. Then, the termination time is equal to the final time which is closest to the future time. Here, N is defined as the time interval between current time and the termination time. To sum up, the cascade hydropower stations should carry out the pre-discharge scheduling during the time interval N, and the normal operation after termination time. Moreover, the water level of each reservoir needs to return to the high water level in the termination time. Steps of pre-discharge scheduling are as follows:

Step 1: The average discharge $\bar{Q}$ that can guarantee that the water level of Liyuan Hydropower Station reaches the high water level at the termination time is determined. Then, it is assumed that Liyuan Hydropower Station generates electricity using $\bar{Q}$, while the other five hydropower stations downstream generate electricity only by use of actual flow, and these five reservoirs' storage remains unchanged. Based on this assumption, the operation rules of the cascade hydropower stations are given:

(1) If there is surplus water released from the Liyuan Reservoir, the Liyuan Reservoir should generate the expected output power during the forecast period. In other words, the inflow of the Liyuan Reservoir is relatively abundant.

(2) If the Liyuan Reservoir has no surplus water while the other five reservoirs downstream have, the Liyuan Reservoir should generate electricity with $\overline{Q}$ in every time interval during the forecast period, and the operation of the downstream stations will be further formulated.

(3) If all the reservoirs have no surplus water, the minimum discharge $Q_{\min}$ that can guarantee that the water level of the Liyuan Reservoir reaches the high water level at the termination time is determined under the condition that the other five reservoirs downstream have no surplus water when generating electricity with the actual inflow. $Q_{\min}$ is regarded as the discharge of the Liyuan Reservoir in every time interval during the forecast period. For the Liyuan Reservoir, if the output generated by $Q_{\min}$ is less than the basic required output, Liyuan Hydropower Station must run in accordance with the basic output requirements.

Step 2: The sum of the discharge of the Liyuan Reservoir and the corresponding predicted local inflow is regarded as the inflow of the hydropower stations downstream.

Step 3: The hydropower stations downstream are treated as a new cascade. The discharge of Ahai Hydropower Station in each time interval during the forecast period is obtained using the method used for Liyuan Hydropower Station. Similarly, the discharges of the other four hydropower stations, Jinanqiao, Longkaikou, Ludila, Guanyinyan, during the forecast period, are calculated.

The specific calculation process and formulas are shown in Fig. 2. In Fig. 2, $\overline{Q}_i$ is the average discharge that can guarantee that the water level of the *i*th hydropower station reaches the high water level at the termination time; Q_i^{ex} is the runoff of the *i*th hydropower station needed for generating expected output; $Q_{i,j}^{\mathrm{na}}$ is the natural inflow of the *i*th hydropower station in the *j*th time interval obtained by the runoff prediction; W_i is the change value of storage capacity of the *i*th hydropower station during the time interval *N*, and usually zero or negative; $Q_{i,j}^{\mathrm{al}}$ is the allowed discharge of the *i*th hydropower station in the *j*th time interval; $Q_{s,j}^{\mathrm{lo}}$ is the local inflow of the *s*th hydropower station in the *j*th time interval; $q_{i,t}$ is the discharge of the *i*th hydropower station in the *t*th time interval; $q_{i,j}^{\mathrm{in}}$ is the discharge of the *i*th hydropower station in the *j*th time interval for the initial scheduling decision; Q_i^{gu} is the discharge of the *i*th hydropower station that meets the basic output requirements; $Q_{i,j}^{\mathrm{d}}$ is the final discharge flow of the *i*th hydropower station in the *j*th time interval; *m* is the number of cascade hydropower stations ($2 \le m \le G$); $Z_{i,j}$ is the water level of the *i*th hydropower station in the *j*th time interval; and $Z_{i,j}^{\min}$ and $Z_{i,j}^{\max}$ are the minimum and the maximum allowed water levels of the *i*th hydropower station in the *j*th time interval, respectively.

When using the formulas in Fig. 2, we need to pay attention to the following:

(1) When calculating Q_i^{ex}, the upstream water level of the reservoir is the average value of the water level at the current time and the expected water level at the end of the scheduling time. Generally, the expected water level is the normal water level and the limited water level in the flood season.

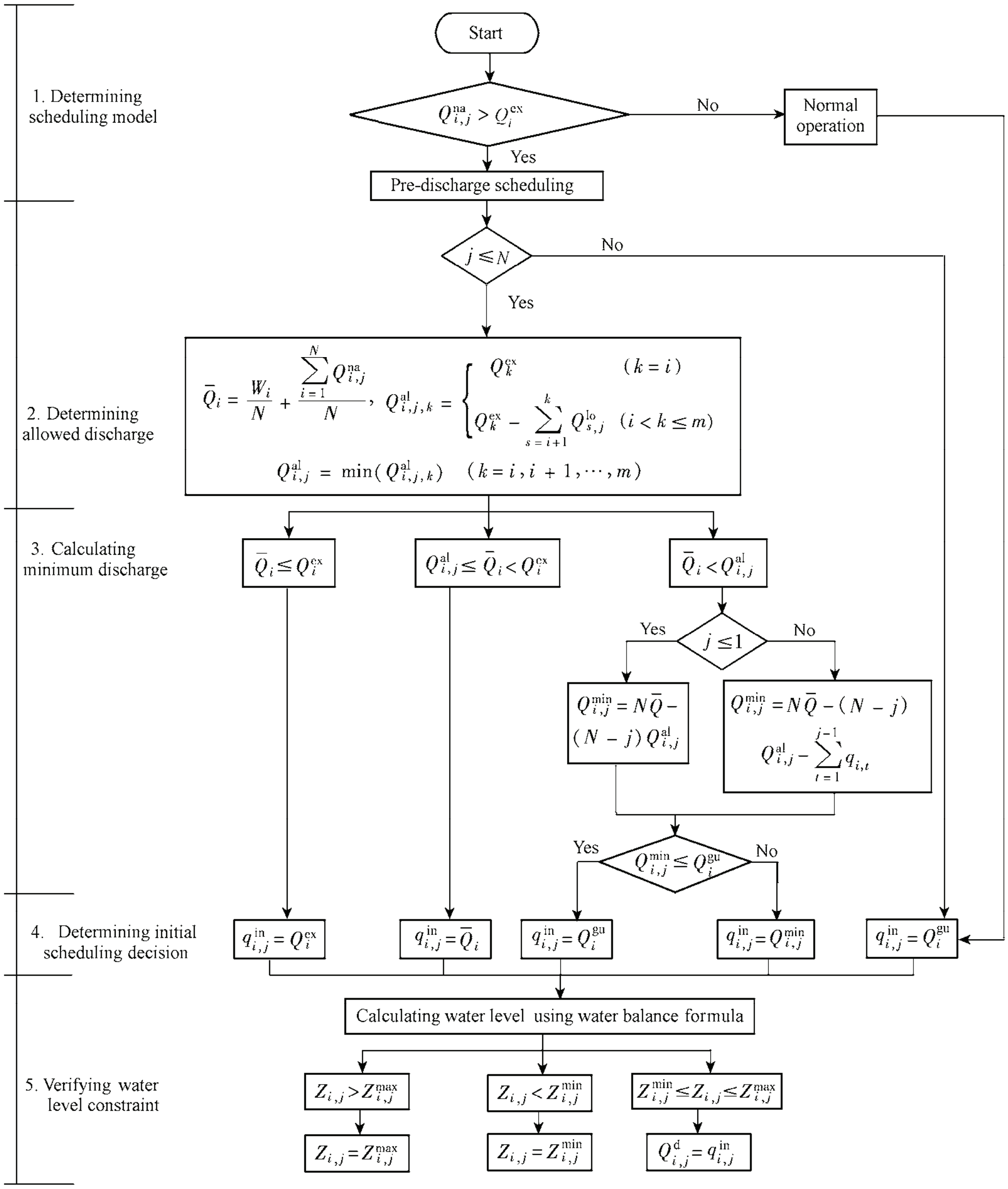

Fig. 2 Calculation process and formulas during general period

(2) In terms of the generation scheduling of the downstream station, the predicted inflow is actually the sum of the discharge of the farthest upstream station and the corresponding predicted local inflow.

(3) The calculation order of $q_{i,t}$ should be from the farthest upstream station to farthest downstream station according to chronological order. In other words, it is not until all discharges of the ith station during forecast period have been obtained that the calculation for $(i+1)$th station is carried out.

4.2.2 Rules during dry-flood transition period

Based on Table 1, it is clear that almost all hydropower stations have the limited water level in July. Guanyinyan Hydropower Station has the limited water level in August as well. Through analysis of the optimized operation results, it is known that before the flood season in July, even in a wet year, the water levels of these six hydropower stations can regress from the normal water level to the limited water level through increasing output in around a total of 17 days. To better explain the length of the dry-flood transition period which is a variable mentioned above, an example is given: Suppose that the water levels of cascade hydropower stations can regress from the normal water level to the limited water level in five days before the flood season in July, then the period from June 25 to June 30 is identified as the dry-flood transition period. Thus, it is easy to learn that the dry-flood transition period of the cascade in this study is June 13-30. This dynamic partitioning is simple and universal.

The scheduling rules during the dry-flood transition period are as follows:

Step 1: As the limitation of short-term runoff forecast, the forecast period is shorter. Taking into account the feasibility and applicability, the average discharge in the forecast period is regarded as the average discharge in the time interval M. Here, M is the time interval between the current time and the starting time of the flood season.

Step 2: The required time that the water level of these six stations regresses from the current level to the limited level is calculated when Guanyinyan Hydropower Station runs with the flow discharge needed for generating the expected output power.

Step 3: If the required time is shorter than M, the scheduling rules are the same as those during the general period. Otherwise, the rules during the dry-flood transition period are as follows: the farthest downstream station of the cascade (Guanyinyan Station) generates the expected output power, and the other five stations upstream generate electricity all by using the maximum discharge that can ensure that the next station has no surplus water. It must be noted that the order of scheduling should be from upstream to downstream.

The specific calculation process and formulas are shown in Fig. 3. In Fig. 3, $\overline{Q}_{\mathrm{m}}$ is the average discharge needed when the water level of the farthest downstream station (Guanyinyan Station) declines to the limited water level, Q_{me} is the discharge of the farthest downstream station that can generate the expected output, T_1 is the runoff forecast period, K is the total time interval between current time and the starting time of flood season, T' is the time needed for the water levels of all reservoirs to regress from the current water level to the limited water level when the farthest downstream station generates the expected output, and T_{u} is the length of the unit time interval.

5 Results verification

The data used is the daily runoff process within three typical years and a large number of simulated daily runoff processes. The computational processes have been given in Section 3.

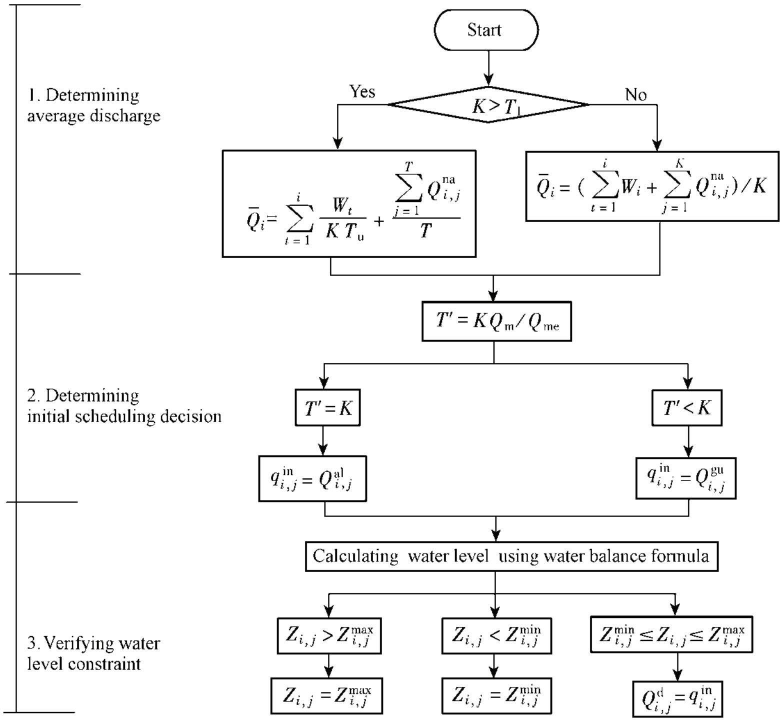

Fig. 3 Calculation process and formulas during dry-flood transition period

In this study, the results of the normal year are shown in figures for analyzing the operation processes. Comparison of the simulated operation processes of all hydropower stations based on the scheduling rules and the optimized operation processes obtained by the hybrid algorithm are shown in Fig. 4. However, these figures mostly refer to the processes between June and September because the scheduling processes of other months are almost unchanged. In other words, the water levels basically remain at the high water level. The comparison of power generation in three typical years is listed in Table 2 as well.

Table 2 Comparison of power generation in three typical years

Hydropower station	Annual power generation (10^8 kW·h)								
	Wet year			Normal year			Dry year		
	Optimized operation	Simulated operation	Relative difference (%)	Optimized operation	Simulated operation	Relative difference (%)	Optimized operation	Simulated operation	Relative difference (%)
Liyuan	109.500	109.223	–0.25	97.639	97.479	–0.16	75.803	75.477	–0.43
Ahai	91.853	92.023	0.19	82.042	82.368	0.40	60.887	61.179	0.48
Jinanqiao	125.578	125.877	0.24	113.401	113.610	0.18	88.588	88.510	–0.09
Longkaikou	85.287	84.920	–0.43	75.738	75.282	–0.60	56.323	55.762	–1.00
Ludila	103.411	103.302	–0.11	92.775	92.577	–0.21	68.819	68.548	–0.39
Guanyinyan	146.104	145.268	–0.57	131.530	130.449	–0.82	94.958	94.316	–0.68
Total	661.732	660.613	–0.17	593.124	591.764	–0.23	445.388	443.791	–0.36

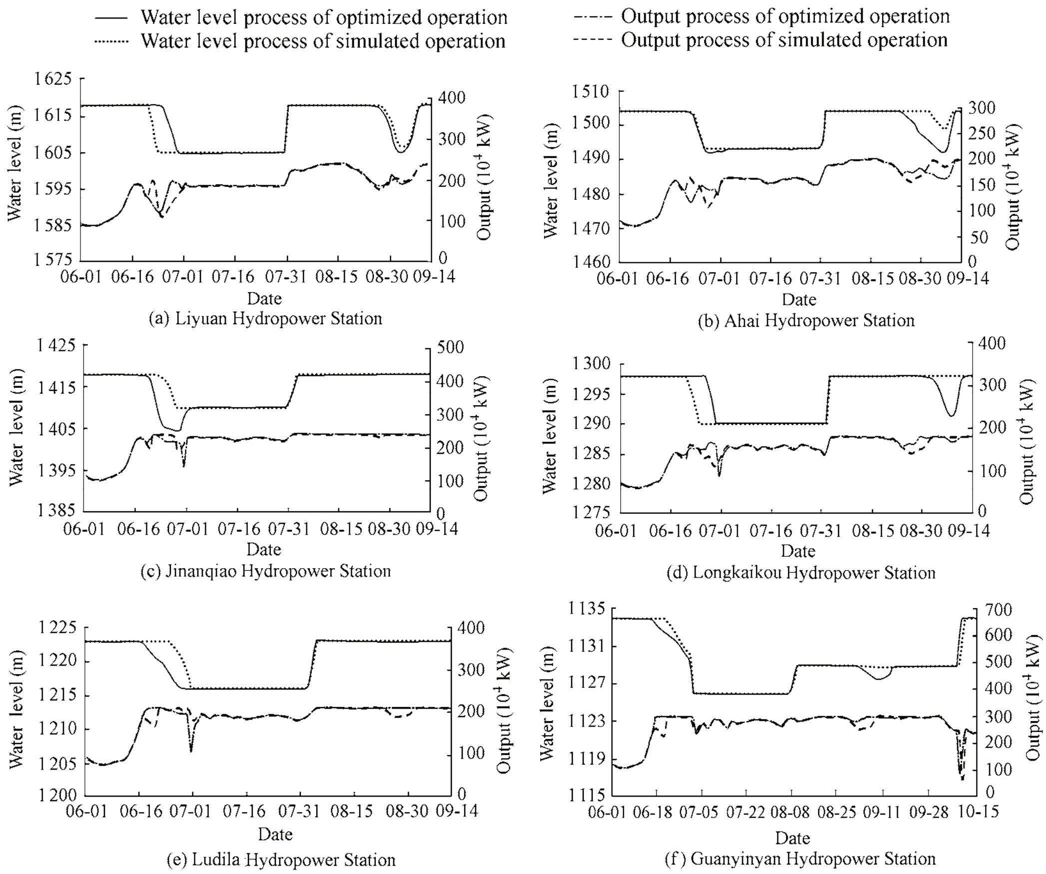

Fig. 4 Comparison of optimized operation processes with simulated operation processes

The following observations are made from the comparative study of the simulated operation and the optimized operation:

(1) It is concluded from Fig. 4 that the output processes and the water level processes of all hydropower stations according to scheduling rules are basically the same as those optimized results.

(2) Regarding to Liyuan Hydropower Station (Fig. 4(a)) and Longkaikou Hydropower Station (Fig. 4(d)), the starting time of pre-discharge scheduling of simulated operation is June 22 or so, while the starting time is around June 25 for optimized operation. Owing to the water levels of the two hydropower stations prematurely regressing from the normal water level to the limited water level, power generation from the two stations decreases. As shown in Table 2, the power generation decrease 0.16×10^8 kW·h at Liyuan Hydropower Station, 0.456×10^8 kW·h at Longkaikou Hydropower Station, and 1.081×10^8 kW·h at Guanyinyan Hydropower Station in a normal year. Another reason for the power generation reduction of Longkaikou Hydropower Station may be that the pre-discharge scheduling is not adopted between August 30 and September 15. With regard to Guanyinyan Hydropower Station (Fig. 4(f)), the main reason for the power generation reduction may be that the pre-discharge scheduling is not adopted

between August 25 and September 10.

(3) Increase in the power generation of simulated operation at Ahai Hydropower Station (Fig. 4(b)) and Jinanqiao Hydropower Station (Fig. 4(c)) may be attributed to the better control of the water level during the flood season. For example, the water level of Jinanqiao Hydropower Station decreased from 1 418 m to 1 405 m when the optimized operation was adopted between June 20 and July 1, while it decreased only from 1 418 m to 1 409.9 m when the simulated operation was adopted between June 16 and June 24. As shown in Table 2, the power generation increases 0.326×10^8 kW·h at Ahai Hydropower Station, and 0.209×10^8 kW·h at JinAnqiao Hydropower Station in a normal year.

(4) All hydropower stations have adopted the joint pre-discharge scheduling before the cascade hydropower stations enter into the flood season according to the runoff prediction.

(5) It can be shown from Table 2 that the results of annual power generation obtained by the scheduling rules are quite close to the optimized operation results. For a single hydropower station, the minimum relative difference of annual power generation is only 0.09% (Jinanqiao Hydropower Station in a dry year), and the maximum is also no more than 1% (Longkaikou Hydropower Station in a dry year). For cascade hydropower stations, the maximum relative difference of the total annual power generation is just 0.36% (in a dry year), and the relative differences in a wet year and normal year are smaller.

6 Conclusions

Through analysis of large numbers of optimized scheduling processes, this study highlights the short-time power generation scheduling rules for cascade hydropower stations. After further refining and summarizing these rules, a set of simple and practical formulas are eventually provided. Compared with many previous studies, the principle of the rules is so clear that it is easy to understand and the feasibility is relatively high. Moreover, compared with the optimized operation, these rules have high accuracy with a relative difference of less than 1% in annual power generation. Being different from the conventional optimal generation rules for hydropower stations, the rules can take full advantage of the rolling runoff forecast and carry out the rolling scheduling. In this way, the prediction error of a runoff forecast can be revised, and the negative impact on power generation dispatching is effectively reduced. The accuracy of the results is verified by a case study. Furthermore, the application of these formulas can be easily extended because of the simple form and specific meaning. Therefore, this study provides a new perspective in formulating the rules of power generation dispatching.

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