Joint optimization of cascades in Yalong River and the middle and downstream of Jinsha River

ZHANG Hairong^{1,a}, LI Peng¹, REN Yufeng¹, LIANG Zhiming¹, CHEN Yufan¹, LI Chunlong²

¹China Yangtze Power Co., Ltd., Yichang 443133, China

²China Three Gorges Projects Development Company Limited, Chengdu 610041, China

Abstract. The main tributaries of the upper reaches of the Yangtze River are not only the strategic base for China's water resources, but also an important hydropower base for the “West-East Power Transmission Strategy”. With the completion of these reservoir groups, a large-scale mixed reservoir system across the different basins has been formed, which makes the requirements for joint optimization and scheduling of large-scale hydropower system getting higher and higher. This paper focuses on the key problems faced by the joint optimization of large-scale hydropower system in the basin. Taking the Yalong River and the middle and downstream of the Jinsha River as the research area, the hybrid optimization method is introduced herein to solve the joint optimal scheduling model. The results reveal that the power generation by joint optimal scheduling is much more than separately scheduling, and the total power generation increased by 2.84% on average. As Mid-Jinsha cascade and Yalong River cascade has a 690 million kW·h and 190 million kW·h decrease in power generation respectively, the downstream Jinsha River cascade has a power generation increase of 4.31 billion kW·h.

1 Introduction

As the longest river in China and even in Asia, The Yangtze River has abundant water resources. Among the “Thirteen Hydropower Bases” planned by China, the Yangtze River Basin has five bases, namely the Yalong River, the Jinsha River, the Dadu River, the Wujiang River and the upper reaches of the Yangtze River. With the implementation of “China Western Development” and “West-East Power Transmission Strategy”, the southwest hydropower base continues to develop, and the main tributaries of the upper reaches of the Yangtze River have completed some control reservoirs such as Jinpingyiji, Ertan, Xiluodu, Xiangjiaba. The reservoirs such as Lianghekou, Wudongde and Baihetan will also be completed and put into operation around 2020^[1].

However, as these control reservoirs belong to different owners, their scheduling modes and main objectives are different, which makes joint scheduling difficult. At present, the reservoir scheduling theories and methods are mostly limited to single reservoir or cascade reservoirs. The scale involved is small and the scheduling targets are relatively simple. It is difficult to be adapted into the joint scheduling of the large-scale reservoir groups under the comprehensive utilization requirements such as flood control, power generation, water supply and so on^[2-3].

Among those optimization methods, the Large System Decomposition and Coordination (LSDC) optimization method uses decomposition and coordination mechanisms to decompose complex optimization

problems into a series of simple sub-optimization problems, thus decoupling complex problems^[4-5]. The Discrete Differential Dynamic Programming (DDDP) method divides the huge solution space into many subspaces through the decision domain decomposition mechanism, and realizes the computational complexity from exponential growth to linear growth^[6-8]. Further, relevant scholars combined LSDC and DDDP to the optimal operation of water resources systems, and achieved excellent results^[9-10].

In this study, firstly we conduct the modeling and solution method study of large-scale hydropower system. By taking the 24 stations in the Mid-Jinsha River, Yalong River and downstream Jinsha River cascades into consideration, a joint optimization scheduling potential analysis is conducted on these three cascades. Meanwhile, in order to explore the different impacts of different joint optimization scheduling combinations on power generation, the advantages and differences between the five modes of individual power station scheduling and separate joint scheduling in each river basin are compared. The prospect of joint optimization scheduling in the upper reaches of the Yangtze River is analyzed.

2 Study area and research methods

2.1 Study area

The Yangtze River has a total length of about 6,400km, and a control basin area of 1.8 million km². The Yangtze

^a Corresponding author: zhang_hairong@ctg.com.cn

River Basin has a warm climate, abundant rainfall and abundant water resources. The average annual runoff is about 960 billion m³, accounting for 36% of the total runoff in China. In addition, the Yangtze River Basin has developed water systems with numerous tributaries, and it has a large natural gap and abundant water resources. The theoretical reserves amount to 268 million kW and the developable capacity is 197 million kW. Among them, the hydropower resources in the upper reaches of the Yangtze River are particularly prominent, and its theoretical reserves and developable quantities account for 80% and 87% of the total watershed respectively. The Yalong River and Jinsha River hydropower bases, which belong to the “Thirteen Hydropower Projects” planned and constructed in China are major parts of China's western development and the strategy of sending power to the east. The distribution of the power stations in the basin at present is shown in Figure 1.

Figure 1. The distribution of the power stations in the upper Yangtze River in China.

2.2 Optimization model

The long-term optimal scheduling is to reach the maximum power generation of large-scale hydropower system over the whole operation periods within some equality and inequality constrains. In general, the objective and constrains of long-term optimization of large-scale hydropower system are expressed as follows:

(1) Objective function

Considering the maximum total power generation of the reservoir group as the optimization target, the mathematical description is as follows:

$$\max F = \sum_{i=1}^M \sum_{j=1}^T N_{ij} \Delta t = \sum_{i=1}^M \sum_{j=1}^T A_i H_{ij} q_{ij} \Delta t \quad (1)$$

where F is the optimization scheduling goals, which is also the total power generation throughout the scheduling period; M stands for reservoir water volume; T represents the number of scheduling periods; A_i is the power generation output coefficient for the i th reservoir; N_{ij} , H_{ij} and q_{ij} denote output, water head and water discharge through hydroturbine of the i th hydro plant in the j th period, respectively.

(2) Constrains

1) Water level constrains

$$Z_{ij,\min} \leq Z_{ij} \leq Z_{ij,\max} \quad (2)$$

where Z_{ij} presents operation water level of the i th hydro plant in the j th period; $Z_{ij,\min}$ and $Z_{ij,\max}$ are lower and upper water level limits of the i th hydro plant in the j th period, respectively.

2) Water discharge constrains

$$Q_{ij,\min} \leq Q_{ij} \leq Q_{ij,\max} \quad (3)$$

where Q_{ij} presents water discharge of the i th hydro plant in the j th period; $Q_{ij,\min}$ and $Q_{ij,\max}$ are minimum and maximum water discharge limits of the i th hydro plant in the j th period, respectively.

3) Output constrains

$$N_{ij,\min} \leq N_{ij} \leq N_{ij,\max} \quad (4)$$

where N_{ij} presents output of the i th hydro plant in the j th period; $N_{ij,\min}$ and $N_{ij,\max}$ are minimum and maximum output limits of the i th hydro plant in the j th period, respectively.

4) Hydraulic connection

$$I_{ij} = \sum_{l \in \Omega_i} Q_{lj} + B_{ij} \quad (5)$$

where I_{ij} and B_{ij} are inflow and local inflow of the i th hydro plant in the j th period, respectively; Q_{lj} is water discharge of the l th hydro plant in the j th period; Ω_i is upper hydro plants set of the i th plant.

5) Water balance equation

$$V_{ij+1} = V_{ij} + [I_{ij} - Q_{ij}] \Delta t \quad (6)$$

where V_{ij} is storage of the i th hydro plant in the j th period; I_{ij} and Q_{ij} are inflow and water discharge of the i th hydro plant in the j th period, respectively; Δt is interval of scheduling term.

6) Water head equation

$$H_{ij} = (Z_{ij} + Z_{i,j+1})/2 - f_{i,zd}(Q_{ij}) \quad (7)$$

where $f_{i,zd}$ is relation function between water discharge and downstream water level of the i -th hydro plant.

7) Water spillage equation

$$q_{ij} + S_{ij} = Q_{ij} \quad (8)$$

where S_{ij} is water spillage of the i th hydro plant in the j th period.

8) Initial and terminal water level

$$Z_{i0} = Z_{i\text{begin}}, Z_{iT} = Z_{i\text{end}} \quad (9)$$

where $Z_{i\text{begin}}$ and $Z_{i\text{end}}$ are initial water level and terminal water level of the i th hydro plant, respectively.

2.3 Strategies of LSDC -DDDP

This research combines the LSDC and DDDP to form the LSDC-DDDP hybrid optimization method to solve the large-scale reservoir group combined power generation optimal scheduling model. Firstly, the large-scale

reservoir group system is decomposed into a series of independent reservoir subsystems. Then, the DDDP method is used to optimize the subsystems. Finally, the coordination direction of each subsystem is coordinated by the coordination factor. The detailed process is as follows:

Step 1: Initialize. According to the topological structure of the reservoir group, the calculation sequence is compiled, and the basic parameters such as the relevant constraint conditions, the maximum evolution algebra and the convergence threshold are determined.

Step 2: Generate an initial solution. According to the requirements of running water and reservoir operation, the corresponding feasible space is obtained, and the initial solution is randomly generated.

Step 3: Calculate the coordination factor. According to the results of the previous generation of the reservoir group, the coordination factors of the current reservoir subsystems are determined.

Step 4: Subsystem initialization. Determine the basic parameters of each reservoir optimization calculation.

Step 5: DDDP initialization. Determine the basic parameters of the discrete differential dynamic programming method.

Step 6: Determine the search corridor. Using the evolutionary results of the previous generations, the current search corridor for each reservoir can be obtained.

Step 7: The i th subsystem optimization. In the case of knowing reservoir coordination factors and optimization corridors, according to the hydraulic linkages between the reservoirs, the DDDP algorithm is used in turn to obtain the local optimal solution of each reservoir.

Step 8: DDDP optimization judgment. If the number of subsystem iterations is not the maximum, goes to Step 6; otherwise, continue to the next step.

Step 9: Subsystem optimization judgment. If the number of power stations is not the largest, goes to Step 5; otherwise, continue to the next step.

Step 10: Optimize the judgment of the reservoir system. Determine whether to continue optimization based on evolutionary algebra and current calculation results. If yes, then goes to Step 3; otherwise, continue to the next step.

Step 11: End. The optimization process of the reservoir group system is terminated, and the optimal solution of the optimal operation of the reservoir group combined power generation is output. ^[10]

3 Results

In order to explore the joint optimization benefits of middle, based on the historical measured runoff data of 1956-2010, the DDDP algorithm and the LSDC-DDDP hybrid algorithm is used to seek the maximum power generation of the middle, downstream of Jinsha River and Yalong River. This paper compares and analyzes ① 24 hydropower stations optimized individually (each hydropower station is optimized by DDDP) ② Three sub-basins optimized respectively (each sub-basin is optimized by LSDC-DDDP) ③ Joint optimization of middle and downstream of Jinsha River basin by LSDC-DDDP ④ Joint optimization of downstream of Jinsha River and Yalong River by LSDC-DDDP ⑤ Joint optimization of middle, downstream of Jinsha River and Yalong River by LSDC-DDDP. The average annual power generation of each hydropower station is shown in Table 1.

Table 1 Comparison of joint optimization scheduling in different combination modes (unit: 100 million kW·h)

cascade/power station		①	②	③	④	⑤
Mid-Jinsha River cascade	Longpan	200.07	196.03	196.03	189.58	189.35
	Liangjiaren	147.25	153.28	153.28	152.36	152.21
	Liyuan	112.65	114.64	114.64	114.32	114.32
	Ahai	94.89	97.36	97.36	97.65	97.67
	Jinanjiao	126.51	135.27	135.27	135.75	135.79
	Longkaikou	84.11	86.15	86.15	86.29	86.32
	Ludila	101.12	104.10	104.10	103.64	103.75
	Guanyinyan	141.85	146.32	146.32	146.74	146.84
	Total	1008.44	1033.15	1033.15	1026.32	1026.25
Yalong River cascade	Lianghekou	144.51	141.87	141.24	141.87	141.43
	Yagenyiji	20.63	20.98	21.12	20.98	21.12
	Yagenerji	53.59	54.84	54.83	54.84	54.88
	Lenggu	150.31	155.17	155.37	155.17	155.41
	Mengdigou	116.96	118.52	118.51	118.52	118.53
	Yangfanggou	79.25	81.01	81.04	81.01	81.05
	Kala	69.20	71.50	71.83	71.50	71.83
	Jinpingyiji	220.86	223.78	218.44	223.78	218.97
	Jinpingerji	296.44	304.77	307.70	304.77	307.69
	Guandi	134.51	136.97	137.34	136.97	137.31
	Ertan	204.43	207.68	206.54	207.68	206.80
	Tongzilin	37.08	37.69	37.90	37.69	37.82

	Total	1527.77	1554.80	1551.86	1554.80	1552.84
downstream Jinsha River cascade	Wudognde	401.88	406.96	409.62	410.94	412.44
	Baihetan	610.88	621.70	629.29	633.45	637.75
	Xiluodu	644.22	662.36	666.33	671.23	674.91
	Xiangjiaba	340.41	353.60	356.11	359.74	362.58
	Total	1997.39	2044.61	2061.35	2075.36	2087.69
Total power generation		4533.60	4632.56	4646.36	4656.48	4666.78
Total power generation increase		-	2.18%	2.49%	2.71%	2.84%

By comparing the average annual power generation of each power station and different combination modes in each basin, the following conclusions can be obtained.

(1) The sub-basin optimized alone can improve the overall power generation of the sub-basin. Through the separate optimization of the middle, downstream of Jinsha River and Yalong River cascades, the power generation of the three sub-basins increased by 2.4, 2.7 and 4.7 billion kW·h compared with the individual optimization of each power station. The power generation of every station has increased in the case of joint scheduling except for the first stations of these basins, and the overall power generation in the three basins has increased by 2.18%.

(2) The joint optimization of power generation in middle and downstream of Jinsha River basin is bigger than that of the joint of downstream of Jinsha River and Yalong River. In the case where downstream of Jinsha River and Yalong River joint schedules, the Yalong cascade power generation reduces 290 million kW·h, while the Jinsha River downstream cascade has a 1.6 billion kW·h increase in power generation. In the case where the middle and downstream of Jinsha River joint schedules, with the help of the massive regulation storage of Longpan reservoir in Mid-Jinsha River, the power generation reduces 680 million kW·h in Mid-Jinsha River cascade, while the downstream Jinsha River cascade has a 3.07 billion kW·h increase in power generation.

(3) We can reach the most significant benefit when Yalong River, Mid-Jinsha and downstream Jinsha River all involved in the joint optimization scheduling. In this case, the Mid-Jinsha cascade has a 690 million decrease in power generation and the power generation reduces 190 million in Yalong River cascade, while the downstream Jinsha River cascade has a power generation increase of 4.31 billion kW·h. This indicates a great potential in the joint optimization scheduling of these three cascades for it greatly increase the amount of power generation in downstream of Jinsha River with a relatively small power loss in the other two cascades, the total power generation of the three cascades increased by 2.84% in comparison with the case when they are individually scheduled.

Figure 2 The increase percentage of power generation by the joint optimization

The increase percentage of power generation by joint optimization scheduling of the 24 hydropower stations (in comparison with the case when they individually scheduled) is shown in Figure 2. In the case when the three cascades joint optimized, the power generation reduces in Longpan, Lianghekou and Jinpingyiji, while the power generation of the other stations has different degrees of increase. With the loss of part of the amount of electricity generated in several leading stations of the cascades, the total power generation of the cascades increase significantly.

4 Conclusions

This paper takes the Mid-Jinsha River, Yalong River and downstream Jinsha River cascades as the research area, and uses the LSDC-DDDP algorithm to solve the joint optimal scheduling problem. By comparing the average annual power generation of each power station and different combination modes in each basin, the results reveal that the sub-basin optimization alone can improve the overall power generation of the sub-basin. The power generation of every station has increased in the case of joint scheduling except for the several first stations of these basins, and the overall power generation in the three basins has increased by 2.18%. The joint optimization of power generation in middle and downstream of Jinsha River basin is bigger than that of the joint of downstream of Jinsha River and Yalong River. In the case where downstream of Jinsha River and Yalong River joint schedules, the Yalong Cascade power generation reduces 290 million kW·h, while the Jinsha River downstream cascade has a 1.6 billion kW·h increase in power generation. In the case where the middle and downstream of Jinsha River joint schedules, the power generation reduces 680 million kW·h in Mid-Jinsha River Cascade, while the Jinsha River downstream cascade has a 3.07 billion kW·h increase in power generation. We can reach

the most significant benefit when Yalong River, Mid-Jinsha and downstream Jinsha River all involved in the joint optimization scheduling, the total power generation of the three cascades increased by 2.84% in comparison with the case when they are individually scheduled.

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