https://doi.org/10.1051/e3sconf/202342302006

Research on Maintenance Boundary Variation of Cascade Hydropower Units Based on Dynamic Programming-Progressive Optimization Algorithm

Liang Zhang[1, *], Wensong Wang[1, **], Yong He[1, ***], Ping Chen[2, ****], Xing Yan[3, *****] and Shuai Lu[1, ******]

[1]Yalong River Hydropower Development Company LTD, Production Management Department, Chenghua, Chengdu, China
[2]Yalong River Hydropower Development Company LTD, Centralized Control Centre, Chenghua, Chengdu, China
[3]Sichuan University, College of Electrical Engineering, Wuhou, Chengdu, China

Abstract. Hydropower, as a primary source of renewable energy, plays a crucial role in achieving the dual-carbon goal. Therefore, it is essential to optimize the maintenance schedule to ensure the smooth operation of hydropower units and explore the principles governing the boundaries of the maintenance window period, considering multiple realistic constraints. In this paper, we take the "3-reservoirs and 7-levels" hydropower station in the lower Yalong River Basin as a case study. We establish an optimal model with the objective of maximizing the generating output, considering the total generating capacity and output of each hydropower station under various constraints. Next, we calculate the number of repairable units based on the ten-day output for each scenario and compare the maintenance window period while analysing its changing pattern. Finally, a comprehensive maintenance plan was developed based on historical maintenance data and industry standards with considering the changing rules. Additionally, we provide suggestions based on these rules.

1.Introduction

In response to the global scarcity of fossil energy reserves and the environmental impact caused by their widespread utilization, China has proactively assumed the responsibility of energy conservation and emission reduction. The country has set a dual carbon target and has made significant efforts to transition towards large-scale renewable energy generation. In this regard, hydropower generation stands out as a clean, renewable, and highly efficient energy source with low costs, high power output, and excellent stability. It has emerged as a primary driving force in the realm of new energy generation. By harnessing the power of water, hydropower plays a vital role in China's sustainable energy strategy, helping to mitigate the adverse effects of climate change and promote a greener and more sustainable future.

To make the most efficient use of water resources based on local conditions, multi-level hydropower stations are typically established using basin reservoirs, forming a hydropower station group. Through careful coordination of water levels across each reservoir, the overall benefits of the cascade power stations can be maximized. Furthermore, to ensure the long-term stability of power generation equipment within these plants, it is crucial to establish a well-planned maintenance strategy that promptly addresses potential issues and eliminates hidden dangers. This maintenance strategy must take into account two key factors: water level (including water volume and flow) and equipment condition. By carefully balancing the maintenance window period with the power generation plan, the contradiction between them can be mitigated, thereby ensuring the normal operation of hydropower equipment while maximizing power generation efficiency. Therefore, the determination of the maintenance window period holds great significance for the overall operation of hydropower stations. By properly defining this boundary, hydropower plants can effectively manage maintenance activities, optimize power generation performance, and ensure the sustainable and efficient operation of the hydropower system.

Several literature works have explored maintenance strategies for hydropower stations and provided valuable insights in this field. In [1], the authors discuss the development process of maintenance management for hydroelectric power generation equipment both domestically and internationally. They propose suggestions for optimizing the maintenance management strategy specifically for hydroelectric power generation equipment in China. In [2], a multi-source fault diagnosis method based on Bayesian networks is introduced. This method enables fault diagnosis of hydropower unit components even without state monitoring, thereby enhancing the overall reliability of the system. The coordination of external delivery plans, water level control, and maintenance plans is investigated in [3], which focuses on medium to long-term scheduling research for cascade hydropower stations. This research aims to optimize the scheduling process and improve the overall

---

Corresponding author: *****xingyan0912@163.com,
*zhangliang@sdic.com.cn, **wangwensong@sdic.com.cn, ***heyong@sdic.com.cn, ****chenping21@sdic.com.cn,
******lushuai@sdic.com.cn

efficiency of the stations. [4] presents a Nash Stackelberg game model to calculate the Nash equilibrium point for the maintenance of cascaded coupled hydrothermal power system units. The findings of this study have guiding significance for the arrangement of maintenance scheduling in such systems. Consideration of service age and operating conditions of different components is addressed in [5]. The authors propose a maintenance strategy tailored to different components by combining maintenance resources and scheduling repair activities, thereby optimizing the maintenance process. In [6], a three-dimensional visualization framework based on the virtual digital method of hydropower station equipment maintenance is constructed. This framework enables the quantification of maintenance tasks and other relevant information, ultimately facilitating automatic planning of equipment maintenance under various operating conditions. These literature works provide valuable insights and propose innovative approaches to enhance maintenance strategies for hydropower stations. They contribute to the overall understanding and advancement of maintenance management in the hydropower industry.

However, the above literatures mostly focus on the arrangement of maintenance strategies for components in the unit, without considering the changes in the macro maintenance window period under the influence of factors such as peak load regulation. Therefore, this paper establishes an optimization scheduling model for cascaded hydropower stations firstly, compares the changes in maintenance window periods with different constraints through several cases. Then arranging maintenance plans based on historical maintenance data to obtain the window period. Finally, suggestions are proposed for unit maintenance of cascaded hydropower stations.

2.Establish Optimization Model

2.1Objective Function

For cascade reservoir groups, the objective function can be expressed as

$$E = \max \sum_{i=1}^{R} \sum_{t=1}^{T} A_i Q_i^t H_i^t \Delta t \tag{1}$$

where, i denotes the serial number of the hydropower stations, R is the number of the hydropower stations, t denotes the period order of dispatching time,T denotes the number of time periods. Generally, T=36 is taken as a cycle of 1 year,and it is worth noting that t=1 corresponding to the first ten-day of November,so t=36 corresponding to last ten-day of October in the following year, A_i denotes the power coefficient of hydropower station, Q_i^t and H_i^t denote the generation flow and waterhead of hydropower station i at time t, Δt represents the unit time of dispatching, which is 10 days or 864000 seconds.

2.2Constraint Condition

The objective function mentioned above must satisfy the following constraints.

Water balance of reservoirs

$$V_i^{t+1} = V_i^t + (I_i^t - Q_i^t - S_i^t)\Delta t \tag{2}$$

$$I_{i+1}^t = Q_i^t + S_i^t + I_i^{t,in} \tag{3}$$

where, V_i^t and V_i^{t+1} denote the initial and final capacity of reservoir i at period t respectively, I_i^t,Q_i^t and S_i^t denote inflow, generation flow and surplus water of reservoir i at period t respectively, $I_i^{t,in}$ is the interval flow of reservoir i at period t, I_{i+1}^t is the interval flow of reservoir i+1 at period t.

Constraints of power output

$$N_i^t = 9.81 A_i Q_i^t H_i^t \tag{4}$$

$$N_{i,\min}^t \le N_i^t \le N_{i,\max}^t \tag{5}$$

where, N_i^t denotes the power output of reservoir i at period t, $N_{i,min}{}^t$, $N_{i,max}{}^t$ denote the minimum and maximum power of reservoir i at period t, which can be expressed as a function of waterhead. Special time periods such as the Spring Festival and maintenance of DC transmission channels require additional constraints.

Constraints of reservoir discharging downstream

$$Qdown_{i,\min}^t \le Q_i^t + S_i^t \le Qdown_{i,\max}^t \tag{6}$$

where,$Qdown_{i,\min}{}^t$ and $Qdown_{i,\max}{}^t$ denote the minimum and maximum downstream of reservoir i at period t.

Constraints of reservoir impounded level

$$Z_{i,\min}^t \le Z_i^t \le Z_{i,\max}^t \tag{7}$$

where,$Z_{i,\min}{}^t$ is the lowest water level of reservoir i at period t, usually dead water level, $Z_{i,\max}{}^t$ is the highest water level of reservoir i at period t, usually start water level, a certain water level is reserved when considering flood prevent control.

Finally, all variables mentioned are non-negative.

2.3Flow of DP-POA (Dynamic Programming and Progressive Optimization Algorithm)

2.3.1 Dynamic Programming Algorithm

The dynamic programming algorithm (DPA) has been used in single reservoirs to achieve the water level [7], which as the initial solution for progressive optimization algorithm (POA) to ensure the correctness of results, the specific flow is shown in Fig.1.

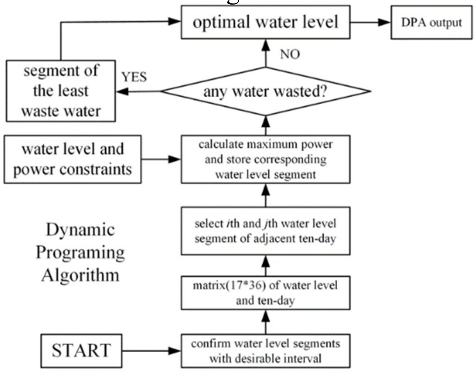

Fig. 1. Dynamic Programming Algorithm flow chart

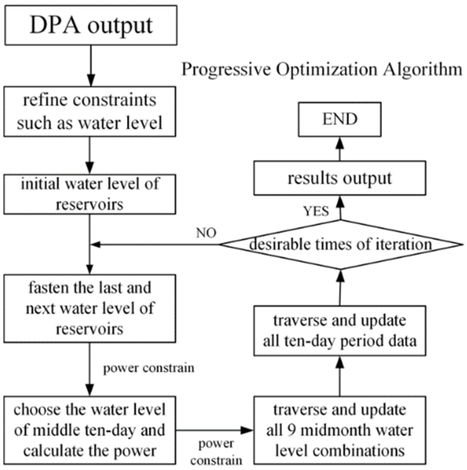

Fig. 2. Progressive Optimization Algorithm flow chart.

2.3.2 Progressive Optimization Algorithm

The water level solved by dynamic programming algorithm are taken as the initial solution for optimization [8], the specific flow is shown in Fig.2.

3.Simulation Results of Maintenance Window Period

In this study, the focus is on the three reservoirs and seven cascade hydropower stations located in the lower reaches of the Yalong River basin in China. Specifically, the reservoirs of *Lianghekou*, *Jinping I,* and *Ertan* have the capability to regulate beyond the seasonal variations, requiring water level control on a ten-day basis. On the other hand, the remaining reservoirs, including *Jinping II*, *Yangfanggou*, *Guandi*, and *Tongzilin*, maintain constant water levels.

To address this, the cascade reservoirs operation model and DPA (Dynamic Programming Algorithm) are employed. The study first solves the water level of each individual reservoir, utilizing DPA. Subsequently, POA (Progressive Optimization Algorithm) is utilized to determine the water levels and power output of the three major reservoirs.

Finally, based on the power output, the study determines the number of repairable units and the maintenance window period. This approach allows for the efficient allocation of maintenance resources and planning of maintenance activities, taking into account the power generation requirements and operational conditions of the hydropower stations.

By employing this methodology, the study aims to optimize the operation and maintenance of the cascade hydropower stations in the Yalong River basin, ultimately improving their overall performance and ensuring the sustainable and efficient utilization of water resources for power generation.

3.1Case with Basic Constraints

Case A takes a normal water year as an example, only considering the basic constraints required for dispatching, such as max and min output constraints, downstream flow constraints, flood control in July, etc. The max output for each period is a function of the corresponding waterhead, and the maximum water head corresponds to the total installed capacity. The min output constraint also known as guaranteed power [9]. An appropriate step is selected to segment the water levels of the three major reservoirs. The relevant parameters and constraints are shown in Table 1-2.

Table 1. Constraints and Parameters of Case A Part I.

Hydropower Station	**Downstream Flow(m^3/s)**	**Flood Constraint of Water Level(m)**	**Guaranteed Power (MW)**
Lianghekou	125	2845.9	1130
Yangfanggou	145	2091	253
Jinping I	373	1859	1086
Jinping II	373	1644	1443
Guandi	200	1328	710
Ertan	401	1190	1028
Tongzilin	422	1013	227

Table 2. Constraints and Parameters of Case A Part II.

Hydropower Station	**Start Level(m)**	**Power Coefficient**	**Installed Capacity (MW)**	**Dead Level(m)**
Lianghekou	2865	8.9	3000	2785
Yangfanggou	2091	8.61	1500	2091
Jinping I	1880	9.18	3600	1800
Jinping II	1644	8.67	4800	1644
Guandi	1328	8.85	2400	1328
Ertan	1200	8.87	3300	1155
Tongzilin	1013	8.97	600	1013

The water level of *Lianghekou*, *Jinping I* and _Er-*tan_ are shown in Fig.3-5. F, M and L denote the first, middle and last ten-day of a month respectively.

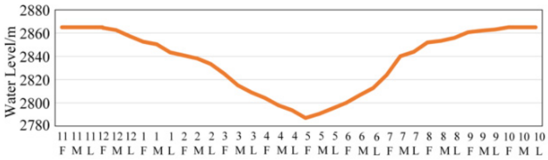

Fig. 3. The water level of *Lianghekou* reservoir

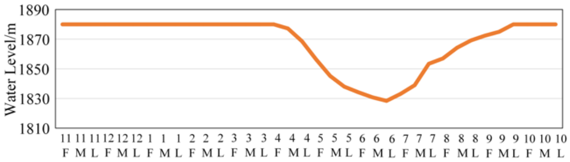

Fig. 4. The water level of *Jinping I* reservoir

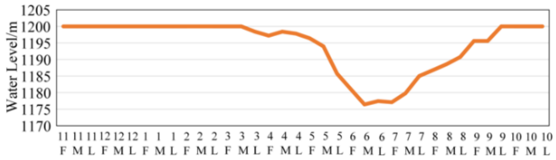

Fig. 5. The water level of *Ertan* reservoir

The corresponding power output is shown in the Fig.6-8.

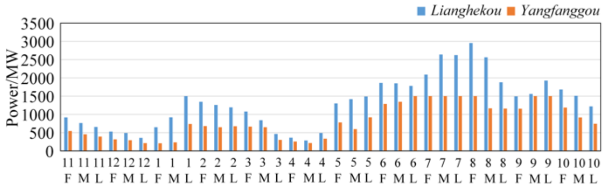

Fig. 6. The power of *Lianghekou* and *Yangfanggou* Hydropower Station

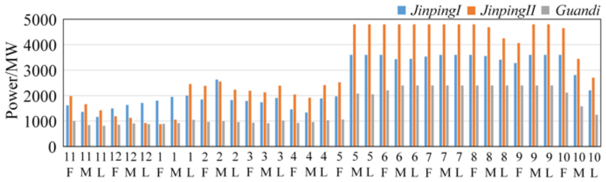

Fig. 7. The power of *Jinping* and *Guandi* Hydropower Station

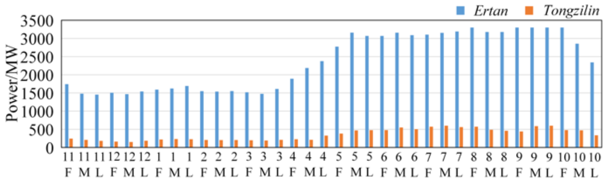

Fig. 8. The power of *Ertan* and *Tongzilin* Hydropower Station

The number of repairable units can be calculated by the following equation:

$$n_{i,e}^{t} = [n_i - P_i^t / p_i] \qquad (8)$$

where, $n_{e,i}^t$ is the number of repairable units of reservoir i at period t, n_i is the number of installed units, P_i^t is the average output of reservoir i at period t, p_i is the feasible capacity of reservoir i at period t, $[x]$ denotes the floor function. The set of time when the number of repairable units isn't zero is called the maintenance window period.

The result is shown in Fig.9, green represents the maintenance window period, red denotes maintenance is forbidden, and the corresponding darker colors in subsequent results indicate an extension or shortening of the window period [10].

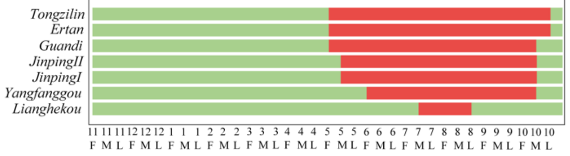

Fig. 9. The maintenance window period of generation set

The total power generation in case A is 102.637 billion kWh. According to the above figure, the station closes to lower reach, the start time of hydro-fluctuation is delayed. *Lianghekou* dissipated to the lowest water level of around 2788m in the first ten-day of May, while *Jinping I* dissipated to the lowest water level of around 1830m in the last ten-day of June. *Ertan* dissipated to the lowest water level of around 1175-1176 m in middle June.

The annual maintenance period of *Lianghekou* and *Yangfanggou* is relatively long, so they can be arranged according to the lowest priority in the case of limited maintenance resources. However, the maintenance period of station closer to the downstream is shorter, and due to the demand for maintenance of 6 units in *Ertan*, it is the most urgent and should be prioritized.

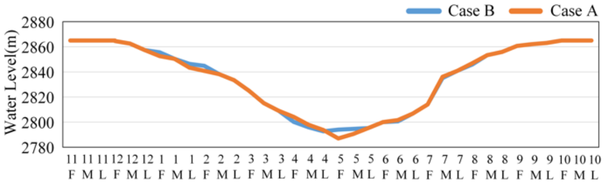

Fig. 10. The water level of *Lianghekou* reservoir (Case A & B)

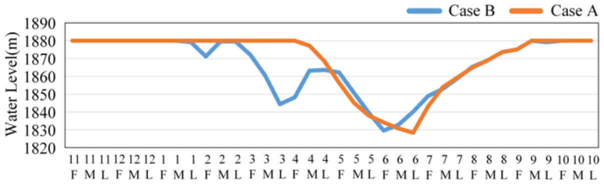

Fig. 11. The water level of *Jinping* reservoir (Case A & B)

3.2Case with All Mentioned Constraints

Case B is obtained by considering power constraints of special period based on Case A, the Spring Festival in February and the maintenance of DC transmission channels compose the special period, as shown in Table 3.

Table 3. Power Constraints with Spring Festival and DC Transmission Channel Overhauled.

Time	Power Constraints of Special Time Period (MW)		
2 First	*Jinping I*≤933.3	*Jinping II*≤1244.4	*Guandi*≤622.2
2 Middle	*Jinping I*≤933.3	*Jinping II*≤1244.4	*Guandi*≤622.2
4 First	*Jinping I*≤500	*Jinping II*≤666.7	*Guandi*≤333.3
4 Middle	*Jinping I*≤500	*Jinping II*≤666.7	*Guandi*≤333.3
5 Middle	*Yangfanggou*≤210		
5 Last	*Yangfanggou*≤210		

The water levels compared with Case A are shown in Fig.10-12. The corresponding power output is shown in the Fig.13-15. The maintenance window period of Case B is shown in Fig.16.

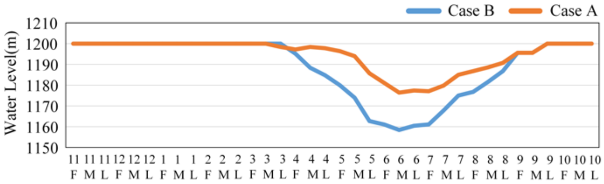

Fig. 12. The water level of *Ertan* reservoir (Case A & B)

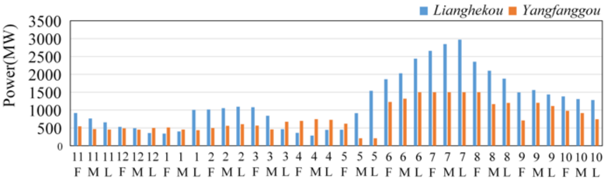

Fig. 13. The power of *Lianghekou* and *Yangfanggou* Hydropower Station (Case B)

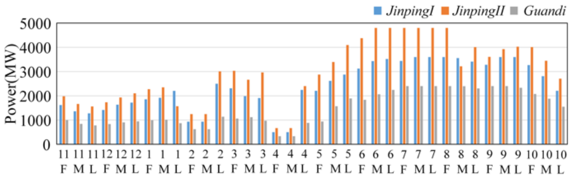

Fig. 14. The power of *Jinping* and *Guandi* Hydropower Station (Case B)

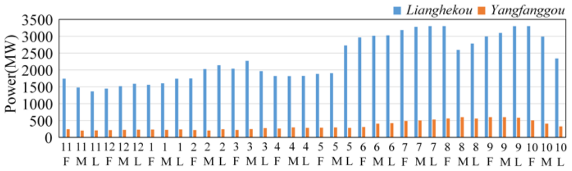

Fig. 15. The power of *Ertan* and *Tongzilin* Hydropower Station (Case B)

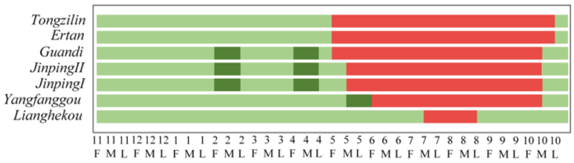

Fig. 16. The maintenance window period of generation set (Case B)

The total power generation in case A is 100.234 billion kWh, which has decreased due to increased restrictions compared with Case A. It also can be seen that before reaching the lowest point of water level in *Jinping* I, there was a phenomenon of back storage in mid-February and mid-April, showing a "W" shape overall, which corresponds to the power constraints during the Spring Festival and the output limit of the *Jinsu* DC transmission channel maintenance period. At this time, passive water storage occurred.

The water levels of the two cases during the wet season from July to October almost coincide. Due to its upstream position, the water levels of the *Lianghekou* hydropower station are slightly lower in case B from December to June than in case A. After June, the two almost coincide, so the overall impact of load limitations is relatively small. However, due to the limited output of the upstream *Jinping I* station, the *Ertan* station located downstream has a faster dissipation speed compared to case A to fill the "missing" part of the output, and the lowest point of the water level is relatively smaller, which is greatly affected by the maintenance of the upstream power station's DC transmission channel.

The changes in maintenance window period caused by DC transmission channel maintenance and Spring Festival load restrictions are reflected in the corresponding increase in the number of maintenance units per ten days, generally increasing by 1-2 units, and *Jinping II* increasing by 2 units. The start and end time of unit maintenance change inconspicuously.

3.3Case B with Load Peak Regulation

Based on the water level and output results of Case B, peak load regulation is considered. At this point, the water level is as same as Case B, and the output only needs to be additionally accumulated for fixed peak load, as shown in Table 4.

Table 4. Extra Peak Load of 7 Hydropower Stations.

Hydropower Station	Extra Peak Load (MW)
Lianghekou	400
Yangfanggou	180
Jinping I	170
Jinping II	310
Guandi	120
Ertan	400
Tongzilin	50

The maintenance window period of Case C is shown in Fig.17. The impact of peak load regulation on the maintenance window period is mainly reflected in the decrease maintenance unit number during the dry and normal periods, which in each ten days is generally reduced by 1 unit (2 units for *Jinping II*). The upstream *Lianghekou* and *Yangfanggou* station have a large margin for peak load regulation to undertake more tasks, so the number of maintenance units can be significantly reduced; The change in the number of repairable units of the downstream 5 hydropower stations is relatively small, as it has already undertaken most of the power generation tasks, especially in *Ertan*, which has the shortest window period. Therefore, it is recommended to prioritize arranging peak load regulation for the upstream two stations.

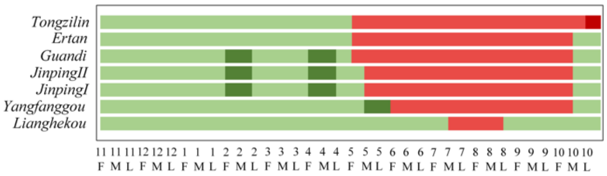

Fig. 17. The maintenance window period of generation set (Case C)

4.Simulation Results of Maintenance Schedule Planning

In this section, the maintenance plans according to historical data of *Yalong River* basin and China occupation standards *DL/T 1246-2013* based on window period calculated in section III are compared, the time required for maintenance at different ranks of each hydropower station are shown in Table 5. The number corresponds to its maintenance ranks, and the sum for different maintenance ranks is the number of installed units.

Table 5. Time Required Maintenance of Different Ranks Based on History Data and Occupation Standards.

Hydropower Station	Historical Data	Occupation standards
Lianghekou	no data	A:80 days each, 8-10 years for cycle B:70 days each, can be arranged between two adjoin A C:15 days each, 1 year for cycle
Yangfanggou	4, C:30 days each	
Jinping I	6, C:20 days each	
Jinping II	8, C:15 days each	
Guandi	3, C:30 days each 1, A:120 days each	
Ertan	5, C:30 days each 1, A:100 days each	
Tongzilin	3, C:30 days each 1, A:130 days each	

4.1 Considering Maintenance of Rank C Only

According to the specific maintenance tasks of the unit, the maintenance rank can be divided into A, B, C, and D. Rank A includes the most maintenance tasks and requires the longest time. Each unit needs to take at least one C-repair per year [9]. Therefore, the maintenance plan for Section III Case C output results is first arranged based on historical data and occupation standards with a 1-year cycle. The results are shown in Fig.18-19 respectively.

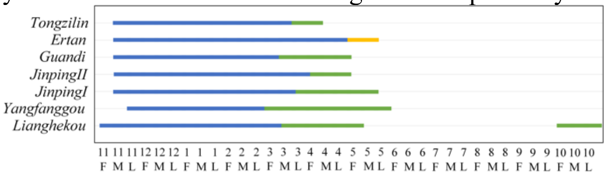

Fig. 18. Maintenance planning results based on historical data with 1-year cycle

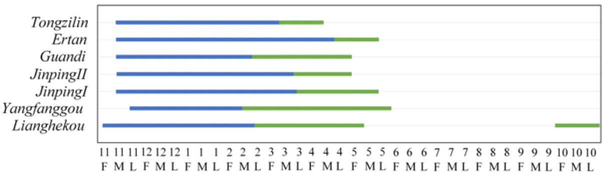

Fig. 19. Maintenance planning results based on occupation standards with 1-year cycle

Green indicates the remaining sufficient time margin after the maintenance is finished. Yellow indicates that the maintenance plan can be met but it is relatively tight. Red represents the time that needs to be extended beyond the existing window period to complete the current maintenance plan, indicating that the current maintenance period is insufficient.

According to historical data the maintenance window period for *Ertan* is relatively short but other stations obtain a large margin. After adopting occupation standards, the maintenance time of *Ertan* has been significantly reduced and get a certain margin.

4.2 Considering Maintenance above Rank C

The maintenance plan with a one-year cycle does not include rank A overhaul, so the plan is arranged based on historical maintenance and occupation standards with a 5-year and 9-year cycle respectively. The results are shown in Fig.20-21 respectively.

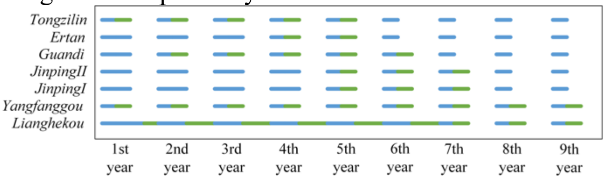

Fig. 20. Maintenance planning results based on historical data with 5-year cycle

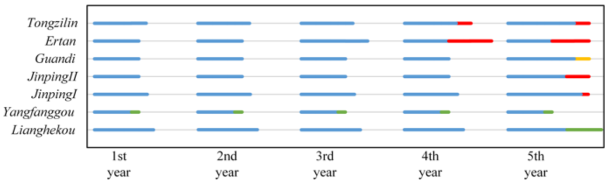

Fig. 21. Maintenance planning results based on occupation standards with 9-year cycle

According to Fig.20, only *Lianghekou* and *Yangfanggou* station can complete the maintenance task based on historical data and a 5-year cycle. *Guandi* barely completes the maintenance, but the window period is tight, and the other stations are unable to complete it. After referring to occupation standards and taking a 9-year cycle in Fig.21, the margin for the window period of Jinping II remains unchanged, while other stations are relatively abundant. The margin of Ertan has increased most significantly so its maintenance tasks can be completed.

5. Conclusion

In this paper, an optimal model for cascade reservoirs is established, focusing on the 3-reservoirs and 7-cascade hydropower stations in the lower reaches of the Yalong River basin in China. The study analyses the change patterns of the maintenance window period under different constraints and proposes corresponding countermeasures. The following conclusions are drawn:

1. Power stations located closer to the downstream, due to a larger inflow of water, bear a heavier power generation task, resulting in a significantly compressed maintenance window period. Most stations have their maintenance window period from February to April. During this period, it is crucial to allocate sufficient manpower and resources to carry out maintenance activities effectively.
2. During the Spring Festival and the maintenance period of the DC transmission channel, the number of repairable units increases by 1-2. On the other hand, during the dry and normal seasons, considering the need for peak load regulation, the overall number of maintenance units is reduced by 1-2, which further compresses the maintenance window period. In such circumstances, it may be feasible to implement dual machine shutdown maintenance.
3. Implementing maintenance based on occupation standards can help reduce the time required for rank A and C repairs, thereby alleviating the tight window period. Conducting a condition assessment can also assist in appropriately reducing the maintenance rank, thereby saving unnecessary time during the maintenance process.

Based on these findings, the paper provides practical suggestions for unit maintenance in cascade hydropower stations. By implementing these recommendations, it is possible to optimize the maintenance window period and improve the overall efficiency and effectiveness of maintenance activities in the hydropower system.

Acknowledgments

This paper is one of the phased achievements of the scientific and technological project Research on Optimization of Maintenance Strategy for Equipment and Facilities of Cascade Hydropower Stations in Yalong River Basin (000023-22XB0071) funded by Yalong River Hydropower Development Company LTD.

References

1. C. Yu, C.L. Yang, Q. Liu, et al. Research on Maintenance Management Strategies for Power Generation Equipment in Domestic and Foreign Hydroelectric Station [J]. Mechanical & Electrical Technique of Hydropower Station,2019,42(12):47-49+87.
2. S. Zhu. A Dissertation Submitted in Partial Fulfilment of the Requirements for the Master's Degree of Electrical Engineering [D]. China Three Gorges University, 2019.
3. C.X. Hu. Coordinated Optimization of Water-level Regulation of Cascade Hydropower Stations, Mid- and Long-Term Maintenance Schedule and Transmission Schedule [D]. China Electric Power Research Institute, 2017.
4. J.R. Dong and M.B. Liu. Research on Unit Maintenance Decision-making Method Based on Nash-Stackelberg Game [J]. GUANGDONG ELECTRIC POWER, 2023,36(04):96-109.
5. R.P. Li. Research on Dynamic Maintenance Planning of Hydroelectric components [D]. Northwest A＆F University, 2021.
6. B.L. Li. Study and Applications on Virtual Simulation and Automatic Planning for Maintenance of Hydropower Equipment [D]. Huazhong University of Science & Technology, 2020.
7. M. Zhang, S.L. Wang, Z.Q. Jiang, et al. Research on Optimal Flood Control Dispatching of the Lower Stung Russie Chrum Hydropower Station Based on Dynamic Programming Algorithm [J]. Water Resources and Power, 2021,39(11):127-131.
8. Z.P. Zhao, S.L. Liao, C.T. Cheng, et al. Discrete gradient progressive optimality algorithm for mid-long-term optimal operation of multi-reservoir system [J]. SHUILIXUEBAO, 2018,49(10):1243-1253.
9. Centralized Control Center of Yalong River Hydropower Development Company LTD. Research report on the cooperative dispatching scheme of the middle and lower reaches of the Yalong River [R]. 2020.12.
10. J. Dai, Y.Q. Jiang, N.J. Tian, et al. Bi-level Optimization for Hydrothermal Unit Maintenance Considering Generation Right Transaction [J]. High Voltage Engineering, 2022,48(10):4143-4153.