Research and practice: key technologies for efficient development and utilization of water power in Dadu River basin

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Abstract: Hydropower development in river basin accounts for a large proportion in China's energy development layout. In order to make efficient use of water power resources and realize green and harmonious development, a set of technical problems such as planning, construction, scheduling and technical reform, which corresponding to hydropower development in the river basin need to be solved urgently. Relying on the Pubugou, Dagangshan, Houziyan, Gongzui, Shuangjiangkou and other projects in Dadu River basin (fifth largest hydropower base in China), a new concept of harmonious development of hydropower in the river basin is proposed through the systematic research and practice. Many typical dam-constructing techniques in large river basin are innovated, and a new way of centralized river basin scheduling and sustainable development of old hydropower stations is explored in this paper. A complete set of hydropower development technologies in large river basin was initiated from planning, construction, scheduling and technical reform. The practice results have been applied to the several cascade hydropower projects construction and hydropower station operation in the Dadu River Basin, which have achieved remarkable economic and social benefits.

Keywords: Dadu River, basin, water power, efficient utilization, harmonious development, key technology

1 Introduction

Hydroelectric power, which converts water energy into electrical energy, is the most important way to utilize water energy. China is the country with the richest hydropower resources in the world, and also one of the countries with the greatest difficulty in development. The *13th five-year plan for hydropower development* has been announced [1]. China's annual hydropower generation accounts for 25% of the world's total, making it the world's largest hydropower production and consumption country. As the second largest conventional energy and the largest clean renewable energy in China, hydropower plays an irreplaceable special role in safeguarding national energy security, implementing the Paris Agreement and building a beautiful China. However, the hydropower development rate in China is only 37%, far lower than the average level of over 75% in developed countries in the world. China's hydropower resources are concentrated in large rivers, and hydropower development in the basin occupies a large proportion in China's energy development layout. Currently, major river basins in China include the upper Yangtze River, Jinsha River, Nu River, Yalong River, Dadu River, Yellow River, Nanpanjiang-Hongshui River, Wujiang River and Brahmaputra river. The total scale of hydropower resources in the ten major rivers is about 380 GW, accounting for nearly two-thirds of the country's hydropower resources. Limited by resource endowment, 80% of China's hydropower development in recent years has been promoted to the areas with deep mountains and valleys, complicated geology, changeable meteorology and sensitive environment in the middle and upper reaches of the basin. The key problems are frequent occurrence of geological disasters, great potential safety hazards, difficulty in quality control, and low level of operation and management. Relying on the Pubugou, Dagangshan, Houziyan, Gongzui, Shuangjiangkou and other projects in Dadu River basin (fifth largest hydropower base in China), the research and practice of key technologies for efficient development and utilization of basin water power were carried out.

2 General situation and characteristics of Dadu River basin

The Dadu river is a typical representative of large river basins in China, with a total length of 1062km and a natural drop of 4175m. 28 cascade hydropower stations with a total installed capacity of 27GW and an annual generating capacity of 115800 GWh have been arranged in the basin. Dadu River basin is one of the thirteen hydropower bases in China and an important part of the flood control system in the Yangtze river basin. The construction and operation of cascade hydropower stations in Dadu River basin have the following characteristics [2]:

(1) Earthquakes occur frequently. The topographic and geological conditions of the Dadu River basin are complex. The overburden thickness is generally 50–120 m. Concealed danger points of major geological disasters (explored at 2212 sites) are distributed in several terraces of the basin. Several seismic fault zones cross the Dadu River basin. For example, the nearest seismic fault zone is only 4 km from the Shuangjiangkou dam site. The maximum designed seismic acceleration at the dam site is 0.557 cm/s^2. The Dadu River basin hydropower facilities face major threats from seismic activity.

(2) The water conditions and weather are complex. The total area of the Dadu River basin is 774 million km^2 with an annual runoff of 47 billion m^3. The basin is in the transitional zone between the Qinghai-Tibet plateau and the Sichuan basin. The upper steppe has a wide extent, and mountains and valleys crisscross the middle and lower reaches. The basin can be affected by several different weather systems. These include the Pacific subtropical high, the Qinghai-Tibet high, the Siberian high, and the southwest warm and wet airflow. The mechanisms of meteorological change are not well understood. The basin is one of the world's most difficult areas for meteorological and hydrological forecasting.

(3) There are many high dams and large reservoirs in the basin. The dam types associated with the cascade hydropower stations in the Dadu River basin include core-wall rockfill, concrete faced rockfill, arch, gravity, and gate. The under constructed Shuangjiangkou dam on Dadu River (height 312m) is the highest one in the world. The reservoir functions include multi-year regulation, annual regulation, seasonal regulation, weekly regulation, daily regulation, and runoff regulation. The

largest reservoir, the Pubugou Reservoir, has a capacity of 5.4 billion m^3. The total reservoir capacity of the basin exceeds 15 billion m^3, which is about 1000 times the water stored in West Lake.

(4) There are various types of power station units in operation in the Dadu River basin (axial turbine, Francis turbine, bulb hydro-generator, and impulse). The number of units under centralized control has reached 41. Although some new equipment has recently been brought into operation, the older equipment has been running for more than 40 years. Thus, there are a larger number of units with a wide variation in age.

(5) The hydropower stations are distributed unevenly. The development methods for the cascade hydropower stations include dams, water diversions, and mixed types. There are 28 planned steps in total. 16 steps of these are under construction or have been built, and are distributed along the 850-km section of the Dadu River trunk stream, and are located in 12 counties (districts), 2 cities, and 3 states in Sichuan Province. There are a large number of different entities involved in the development, management, and operation of the hydropower units. This makes the centralized, unified, and safe and efficient management and control of the hydropower stations much more difficult.

3 Planning concept and development mode

Resettlement and environmental protection are becoming more and more important issues in hydropower development. The traditional development concept is difficult to coordinate the relationship among economic benefit, resettlement and environmental protection. As the fifth largest hydropower base in China, Dadu River has a large population, distinctive ethnic characteristics and profound cultural deposits along its Banks. Its development conditions are greatly restricted by the natural environment and social environment.

3.1 New concept of harmonious development of hydropower in river basin

Under the new situation of hydropower development in the basin, according to the new requirements of resettlement and environmental protection, a new concept of hydropower development in the basin, which is characterized by rational development and utilization of hydropower resources, harmonious and friendly coordination between hydropower development and environment, and harmonious development of hydropower development and society, is put forward systematically. It has been successfully applied to the hydropower development of Dadu River basin [3-4]. First, the basin planning was optimized, and the number of planned cascade hydropower stations was adjusted from 17 to 28. The installed capacity was increased by 4.44 GW, the number of migrants was reduced by 90,500, and the farmland submerged by 28,900 Mu was reduced (Table 1 shows the comparison of some indexes in the three times of hydropower development of Dadu River main stream). The Dadu River basin hydropower planning and environmental planning assessment were highly recognized by all sectors of society. Second, In coordination with the development of hydropower and social harmony, the normal water level of Shuangjiangkou and Houziyan hydropower stations was lowered by 10m. This move has protected national cultural heritages such as culture buildings in Songgang and Danba and preserved some natural river sections and resettlement environmental capacity. Third, the development of hydropower and environmental protection have been coordinated. The first fishway in large basins in China have been built at the Zhentouba-I and Shaping-II hydropower stations, and the transplanting technology for Minjiang cypress, Yew and other rare plants are developed. This move effectively protected the ecological environment of the river basin. Dadu River is becoming a positive example of harmonious hydropower development in large basin of China.

Table 1. Comparison table of some indexes for hydropower development in Dadu River basin

Items	First plan （1977-1990）	Adjust plan （2001-2004）	Optimized plan （2005-2013）	Compare to the first plan
Cascade numbers	17	22	26	+11
Installed capacity（MW）	2150	2340	2594	+4440
Annual production capacity（100 GWh）	1019	1123	1158	+139
Involved population （10 thousands）	21.69	13.23	12.64	-9.05
Submerged cultivated land （10 thousands Mu）	6.27	3.43	3.38	-2.89

Note: the submerged population and cultivated land quantity shall be calculated according to the same benchmark year.

3.2 Cascade development method according to the development plan

In view of the multi-objective decision-making problem of hydropower planning in the basin, on the premise of meeting the technical, economic, immigration, environmental protection and other indicators of the project, it is necessary to seek the non-inferior conversion relationship between economic benefits, environmental protection, and resettlement. By using the multi-objective decision-making model $MAX\left\{ f=(f_1(X), f_2(X), f_3(X)) \right\}$, factors such as resettlement, environmental protection, benefit and decision-making objectives are reasonably set to select the equilibrium solution with the maximum comprehensive benefit, so as to determine the optimal hydropower planning scheme for the basin. This model is used to study the development mode of river basin, and the cascade development is implemented for the first time in large river basin. The original planned single cascade development of Badi, Laoyingyan, Zhentouba, Shaping and other projects was optimized into two cascades respectively. It reduces the reservoir flooding and environmental impact, and promotes the harmonious development of hydropower in the basin. The optimized hydropower cascade layout plan of Dadu river basin is shown in figure 1.

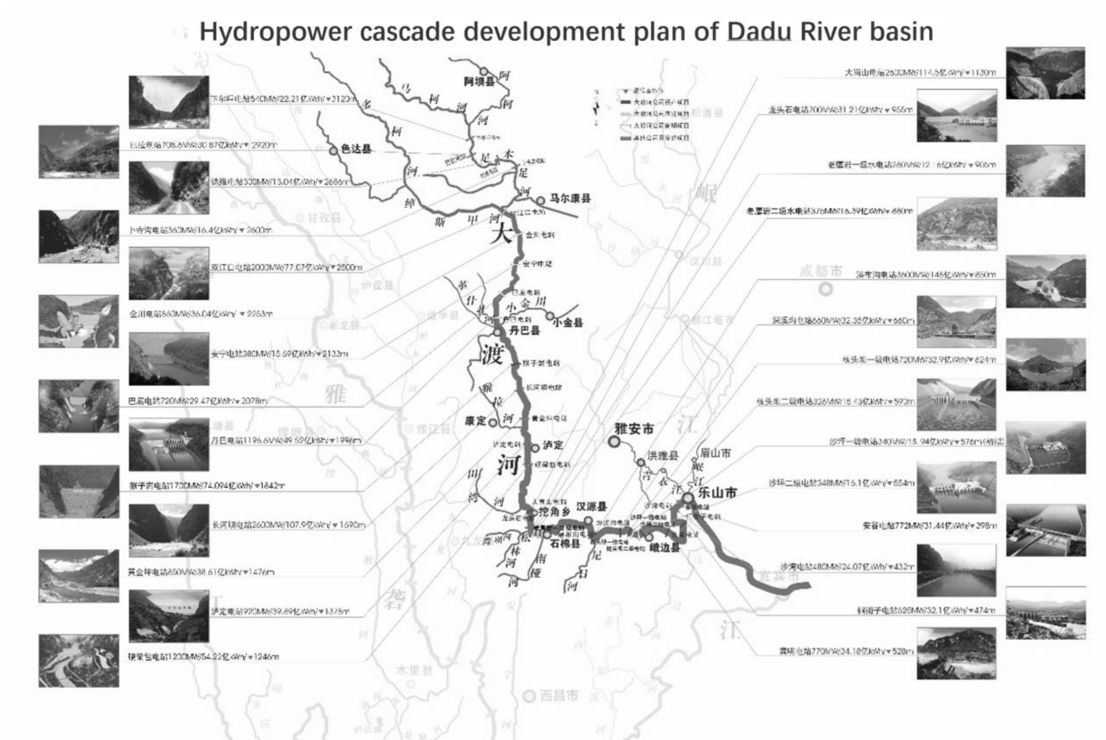

Figure 1. Optimized layout plan of hydropower cascade in Dadu river basin

4 Key damming techniques for different types of high dams

With the deepening of hydropower development, the optional dam site of hydropower project is faced with complex topographic and geological conditions, deep overburden, and high seismic intensity technical problems. In order to realize the harmony and friendship between engineering construction and ecological environment, the technology of high dam is in urgent need of breakthrough [5-6].

4.1 Damming techniques for 200m-level core wall rockfill dam constructed on deep overburden

The Pubugou dam is 186m high and the overburden is 77.5m deep. There are some major technical problems, such as the selection and utilization of wide grading gravel soil, foundation treatment of deep overburden, flood discharge and energy dissipation in deep and narrow river valley with high water head and large flow. For the first time in China, wide graded gravel soil with local clay content of 4.6% was used as seepage control material for the core wall of the dam, which widened the scope of application of dam construction materials and brought remarkable ecological and economic benefits. For the first time, two rigid concrete impermeable walls with large spacing, high strength and low elastic modulus are adopted to connect the core wall with "single wall corridor type + single wall insert type", and the foundation anti-seepage system is innovated (As shown in figure 2). A new type of aeration facility is developed in China, which is the first of its kind in China. The problems of energy dissipation and erosion reduction by aeration are solved.

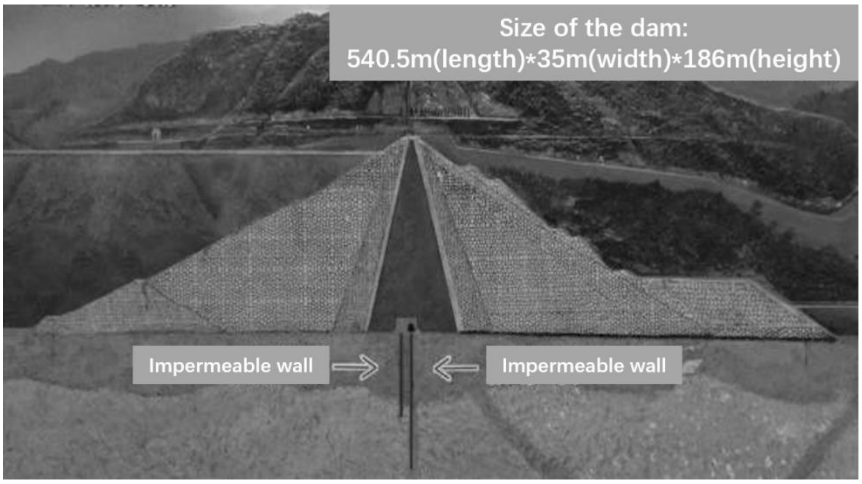

Figure 2. Section diagram of impermeable wall of Pubugou dam

4.2 Seismic safety technology for high arch dams in strong earthquake zones

The Dagangshan double-curvature arch dam is 210m high and located in the ultra-high seismic area. The designed peak acceleration of ground motion is up to 557.5cm/s^2. It is the world's typical extra-high arch dam with a level of 200m, far exceeding the code and the experience of seismic design. The seismic analysis method of arch dam is systematically studied, and the dynamic performance test of dam concrete with full grade bending and tension is carried out for the first time. It provides a basis for seismic code revision. Comprehensive anti-seismic measures to ensure dam safety are put forward and implemented. The anti-seismic safety of high arch dams in the ultra-strong earthquake area is guaranteed by optimizing the shape, laying the anti-seismic reinforcement beams and setting the dampers for the transverse joints of the dam body for the first time. The microseismic monitoring is carried out, which provides a new way for the discussion of the stress and deformation characteristics of the dam body, foundation and abutment and the variation law of the dam through the combination of microseismic monitoring and numerical analysis in the initial period of reservoir storage and dam operation for the first time.

4.3 Damming techniques for concrete faced rockfill dam built on narrow river valleys and deep overburden

Houziyan is a 200m concrete face rockfill dam with the deepest excavation (75m) in the world and the lowest aspect ratio (1:1.25) in the valley at the dam site. In order to solve the technical problem of deep foundation excavation, a new standard for the quality control of the perforation of cofferdam impermeable wall is put forward. In order to effectively deal with the "arch effect" during the filling and compaction construction period of rockfill dam body, the compaction design index of rockfill body that exceeds the specification is innovatively proposed. The GPS quality monitoring system of deep and narrow river valley dam filling and compaction has been developed and applied, which significantly improves the construction quality of the dam. After the dam was put into use, the concrete slab crack was less than 4.0 pieces/(1000m^2), and the maximum accumulative settlement of the dam body accounted for 0.53% of the height of the dam, which was the smallest among the same scale panel dams at home and abroad.

4.4 Damming techniques for 300m-level core wall rockfill dam

In view of the damming techniques for 312m Shuangjiangkou core wall rockfill dam, a series of key technologies are proposed: theory and method of deformation control and stability analysis of dam body and foundation, dam structure type and zoning design, dam dynamic response analysis and seismic measures, dam and plant anti-seepage system layout, soil mining and transportation and automation mixing, surrounding rock stability analysis and rock burst prediction of large underground caverns buried in extremely high ground stress area, design of flood discharge and energy dissipation of high dam and large reservoir in deep mountain canyon area. The orderly implementation of the project construction has promoted the development of the world's super-high earth and rock dam construction technology.

5 Key technology of intelligent integrated dispatching of cascade hydropower station

After the completion of the hydropower station, it is necessary to optimize the basin dispatching to improve the utilization rate of water and energy. At present, the dispatching work is faced with such problems as low accuracy of meteorological and hydrological forecast, difficulty in flood resource utilization, complex power market environment, mismatching of cascade hydropower loads, reliance on manual experience and low dispatching efficiency [8].

5.1 Intelligent forecasting and forecasting technology for the basin

By summarizing the influence law of complex factors in large basin on the prediction accuracy of heavy rainfall, a combined prediction scheme of optimized parameters for short-term numerical prediction and an analysis method for medium and long term rainfall trend were proposed for Dadu River basin (see figure 3 for the distribution of four-layer prediction region in the basin). The multi-scale weather and water situation forecasting model for cascade hydropower dispatching is established, and the first set of intelligent weather forecasting application system for water situation in hydropower industry is developed. The spatial resolution (3km) of rainfall prediction is much higher than the current general resolution (25km), and the accuracy of fixed point and fixed time quantitative prediction of rainfall above 5mm for 24h is up to 0.77, 30% higher than the conventional one.

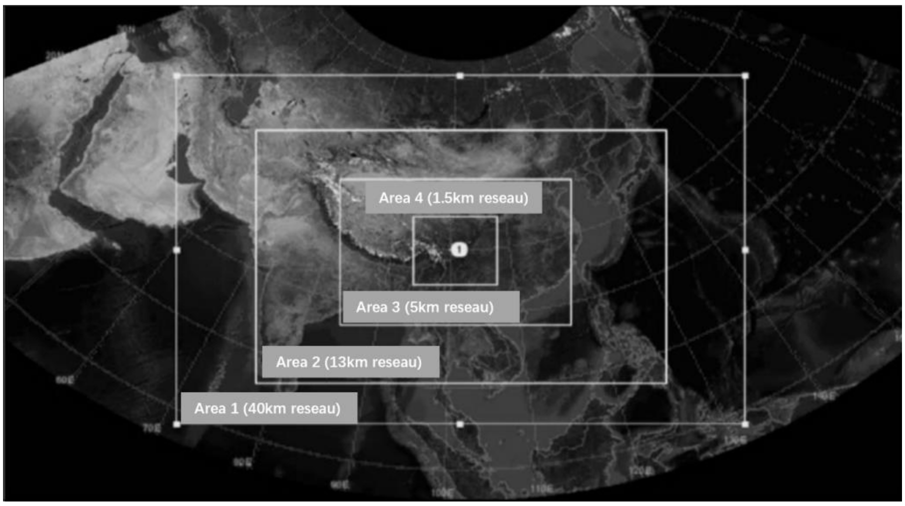

Figure 3. Layout map of four-layer prediction area in the basin

5.2 Identification and resource utilization technology of small and medium floods in river basin

In view of the current situation of extensive traditional flood dispatching mode and low flood resource utilization, the spatial and temporal distribution and evolution rules of floods of different orders in large river basin are summarized, and the risk control model of small and medium-sized flood detention and pre-release is established. According to the characteristics of runoff distribution in Dadu River basin, the storage plan of regulating reservoir in advance at the end of flood season is worked out. In addition, the real-time forecast and operation of the Pubugou reservoir are carried out to tap the potential of flood control and power generation of the reservoir, which improves the utilization of water energy and flood resources in the basin.

5.3 Decision-making method for large basin dispatching based on knowledge reasoning technique

The case base and knowledge base of optimal dispatching of cascade hydropower stations are established, the extraction method of general dispatching rules contained in historical dispatching cases is proposed, the intelligent dispatching decision-making and evaluation model of cascade hydropower stations in the basin is established, and the intelligent dispatching system is developed (see figure 4), which improves the dispatching intelligence level of cascade hydropower stations in the basin. A stable and reliable data acquisition device, which based on pressure type, float type and radar type water level meter, is developed. The software copyrights include automatic collection of electric energy, automatic filling of production data and automatic evaluation of production index process are obtained. The emergency control system of the sluice gate of the large-scale flood discharge facility was invented, and the remote control and emergency self-regulation of the flood discharge facility of the large-scale hydropower station were pioneered.

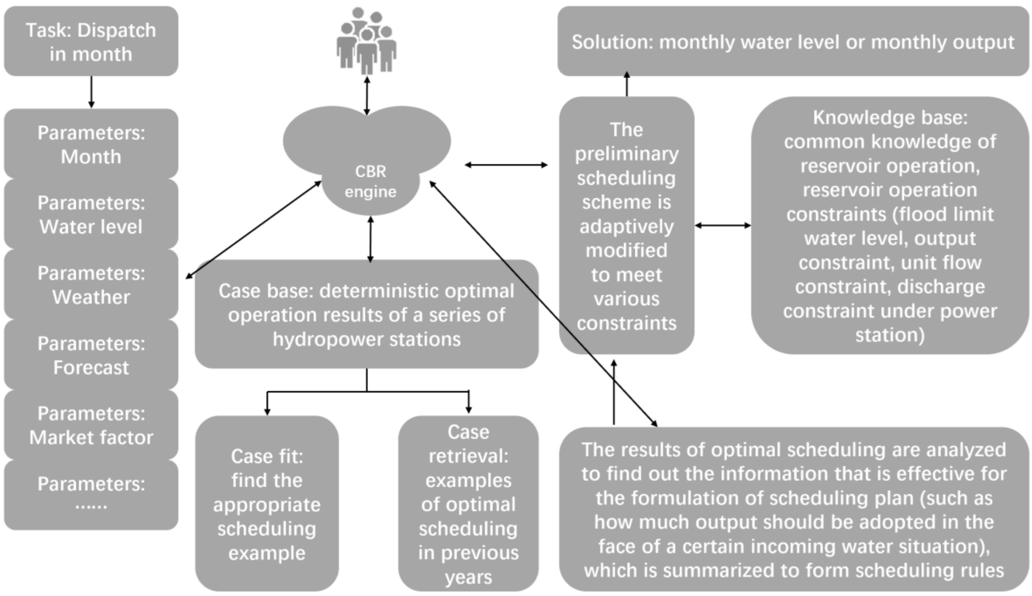

Figure 4. Scheduling decision flow chart with knowledge reasoning technology

5.4 One-key dispatching technology for cascade hydropower stations in the basin

For the first time, a real-time load distribution strategy and a complete set of solving process technology for centralized side cascade EDC based on the layered control principle were developed, and a method for inter-plant joint avoidance of vibration zone was proposed. The real-time dispatching problem involved in AGC joint operation of Pubugou, Shenxigou and Zhentouba stations were studied, and proposes a cascade EDC control strategy under the coordination mode of plant and network. A set of real-time load distribution control model of cascade hydropower station is established, which takes the water level of the runoff hydropower station as the main control object and the overall benefit maximization of the cascade as the goal. An engineering algorithm is introduced to solve the model quickly, and the safety, technology and economy of the technology are verified by the application of Pubugou, Shenxigou, Zhentouba-I projects.

6 Key technology of capacity increase and reconstruction of old units

It is the eternal topic of hydropower development to keep the units running safely and efficiently for a long time and to give full play to the benefits of the power station. In the last century, about 77 GW hydropower stations were put into operation in China. Restricted by the construction conditions and affected by the operation period, many old hydropower stations are faced with many problems, such as insufficient utilization of water, lower efficiency of water energy conversion, and lower safety and reliability.

6.1 Technology of capacity increase and transformation of hydropower station based on systems engineering theory

With the goal of overall optimization, the capacity increase and transformation of 7 units of Gongzui hydropower station and 4 units of Tongjiezi hydropower station have been completed. The unit capacity increased from 0.1 GW to 0.11 GW and 0.15 GW to 0.175 GW respectively, the total installed capacity increased by 0.17 GW, and the weighted average efficiency of the unit increased by 7% and 4% respectively. It not only significantly improves the health level of equipment, but also greatly improves the utilization rate of water and energy resources by improving the unit reference flow and unit efficiency. The problem of mismatching between the reference flow of the hydropower station and the newly invested hydropower station in the basin is solved, and the requirements of the joint economic dispatching of the reservoir group are satisfied. Remarkable benefits of 9200 GWh of annual increase in power generation have been achieved, and a new path for sustainable development of old hydropower stations has been explored.

6.2 Technologies for safe and economical operation of units

Before and after the project, Gongzui unit has experienced three historical stages: the introduction of foreign runner technology, solving the problems left by foreign technology, and independent research and development of new runner. In the process of practice, not only overcome the turbine top cover perforation through independent innovation, which the world-famous hydropower equipment manufacturers failed to solve for many years, but also through joint efforts to effectively promote the domestic turbine design and manufacturing level to catch up with the international advanced level. By means of digital simulation performance prediction, full simulation model test and other advanced technical means, Tongjiezi unit capacity increase and transformation project has effectively solved many unfavorable factors, such as the immovable suction height of water turbine, the immovable nominal diameter of runner and the immovable flow components. 25 MW increase capacity for unit is realized, which creates a record of the largest capacity increase per unit of the axial flow propeller unit at that time. In the course of nearly 20 years, the patented technologies such as quick repair and upgrading for rotor magnetic pole insulation, reactive compensation for generator neutral point, combined lifting of main water engine components of axial flow propeller unit (see figure 5) and single piston three-chamber pneumatic reset brake, have been successively invented and applied, which filled the gaps in the industry.

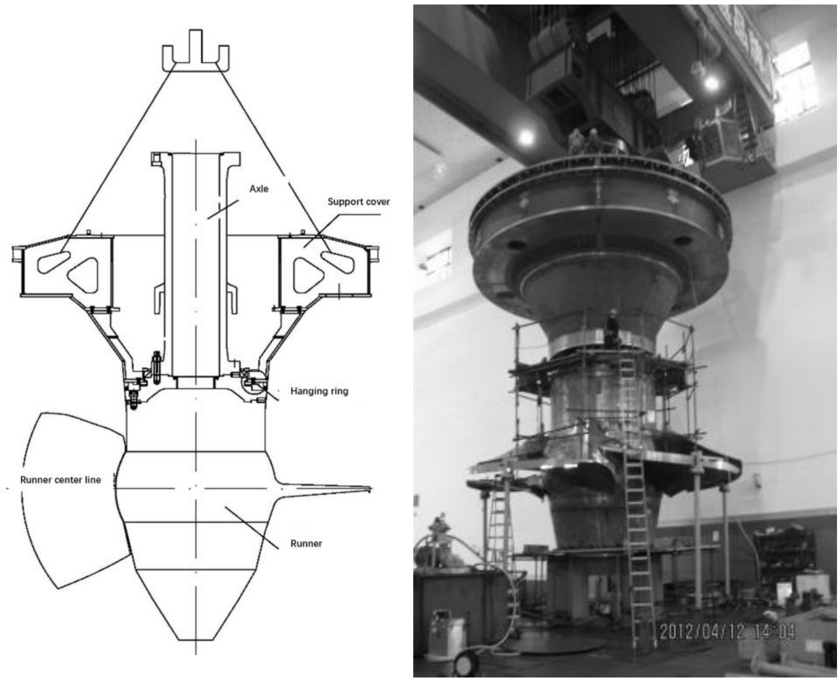

Figure 5. Combined lifting of main water engine components of axial flow propeller unit

7 Conclusions

In order to develop and utilize hydro-energy resources scientifically and realize green and harmonious development, it is urgent to solve the technical problems of planning, construction, dispatching and technological transformation of hydropower development in the basin. Relying on the Pubugou, Dagangshan, Houziyan, Gongzui, Shuangjiangkou and other projects in Dadu River basin (fifth largest hydropower base in China), a set of key technologies for efficient development and utilization of water energy in large river basin from planning, construction, scheduling and technical reform is pioneered. Through the practice of the whole set of technology in the hydropower development process of Dadu River basin, the key problems in the hydropower development planning of large river basin are solved, and the 28 cascades development plan of Dadu River main stream is approved by the government. The problem of wide graded gravel soil as impervious body has been overcome and a set of safety technology system for high arch dam in strong earthquake area has been formed. The technical difficulties in the construction of face rockfill dams in deep and narrow river valleys have been overcome and valuable experience for the development of dam construction technology have been accumulated. The technology progress of 200m high dams has been promoted, and the critical technology gap of 300m high dams have been filled. The first set of efficient dispatching system covering the major power production links such as the prediction, dispatching and evaluation of cascade hydropower stations is constructed in the world. A mature technical system for capacity increase and transformation of old generating sets has been established, which provides valuable experience and technical support for capacity increase and transformation of large and medium-sized hydropower generating sets. With the comprehensive application of the intelligent technology based on the concept of "Cloud, big data, IoT, mobile, intelligent" and the in-depth practice of the management and control mode under the concept of intelligent enterprises [9], the efficient development and utilization of key sets of water energy technologies in Dadu River basin will continue to improve and play a greater role.

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