Research on the Operation of 2 Reservoirs and 3 Stations with Hybrid Pumped Storage Power Station

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Abstract. The hybrid pumped storage power station, utilizing an existing reservoir, is expanded by integrating reversible pump-turbine units. Its operation and scheduling are tightly coupled with the original cascade reservoirs. On the one hand, reversible units, working in tandem with conventional hydropower, are used to complement renewable energy generation, thereby increasing clean electricity output and meeting the grid's peak-shaving needs. On the other hand, scheduling must also balance the demands for mixed pumped storage, downstream reverse regulation, and other operational requirements, making its management inherently complex. This paper analyzes the operational and scheduling characteristics of domestic hybrid pumped storage power stations, with a case study of the Lianghekou hybrid pumped storage power station in Sichuan Province. Aiming to maximize integrated hydropower and photovoltaic generation as well as optimize cascade peak-shaving output, a day-ahead scheduling model for two reservoirs and three stations is developed. Based on simulated operational data from the reservoirs, the study examines the scheduling strategies for both conventional hydropower and hybrid pumped storage power stations under various waterhead conditions throughout the year. Furthermore, a day-ahead operational strategy for the Lianghekou hybrid pumped storage power station, incorporating two reservoirs and three stations, is proposed. The results indicate that under the multi-objective constraints of the new power system, the scheduling of the two reservoirs and three stations follows a clear and regular pattern. The findings provide valuable insights for guiding practical operations.

Keywords: hybrid pumped-storage power station, complementary operation, 2 Reservoirs and 3 Stations

1 Introduction

Hybrid pumped storage power stations(HPSPS), which rely on existing upper and lower reservoirs to expand reversible turbine units, represent a model of pumped storage development characterized by a short construction cycle, minimal environmental impact from reservoir submergence, and low investment costs[1]. This model has significant

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development potential for the future [2]. The operation and scheduling of HPSPS involve two reservoirs and three stations, with complex boundary conditions, high demand for scheduling flexibility, and a comprehensive range of operational requirements,called Hybrid Energy System[3]. Domestic researchers have conducted related studies on hybrid scheduling methods. For example, Guo Aijun et al.[4], Feng Chen et al.[5], and Luo Bin et al.[6] developed short-term joint optimization models for cascaded hydropower stations containing HPSPS, targeting objectives such as optimized peak shaving, maximum power generation, and maximizing overall benefits of the combined system. These studies analyzed the impact of HPSPS on the operational modes of traditional cascade hydropower stations.Further, Cheng Xiong et al.[7] and Tang Haihua et al.[8] developed general models and methods for mid- to long-term joint optimization of reservoir groups containing HPSPS, validating their effectiveness through the Baishan HPSPS. Additional studies by Su Xueling et al.[9], Huang Xiaofeng et al.[10], Li Wenwu et al.[11], and Huang Jingmei et al.[12]focused on maximizing annual power generation, annual peak-shaving benefits, and water resource utilization rates, proposing mid- to long-term optimization strategies for HPSPS.

However, these research findings have not adequately addressed the multi-objective, coordinated operation of two reservoirs and three stations in new power systems, specifically in terms of how hybrid and conventional units operate in tandem under various boundary conditions. Challenges remain in optimizing the reverse regulation function of lower reservoirs under strict scheduling requirements and in leveraging their regulatory capacity. Based on a summary and analysis of the construction and operational characteristics of domestically planned and existing HPSPS, this paper examines the Lianghekou HPSPS in the middle reaches of the Yalong River. The study conducts an in-depth analysis of the combined operation characteristics of conventional and hybrid units across different waterhead sections, as well as the day-ahead scheduling strategies for the two-reservoir, three-station model, providing valuable insights for the coordinated scheduling of conventional hydropower and HPSPS.

2 Study on Operation Modes of HPSPS

2.1 Scheduling Model for Lianghekou HPSPS

Project Overview. The Lianghekou HPSPS utilizes the Lianghekou hydropower station as the upper reservoir and the Yagenyiji hydropower station as the lower reservoir, with an added reversible turbine capacity of 1200MW. The Lianghekou upper reservoir has a capacity of 3000MW and an adjustment volume of 6.524 billion m^3, while the Yagenyiji lower reservoir has a capacity of 300MW and an adjustment volume of 19.69 million m^3.

A significant feature of the Lianghekou HPSPS is that due to the large drawdown depth of the upper reservoir (up to 70m), the important parameters of the pump turbine, the maximum head to minimum head ratio (Hpmax/Htmin), far exceed the upper limit, which can easily cause equipment overload and vibration, and the safe and stable operation of the unit cannot be guaranteed. Therefore, it is necessary to limit the operating range of the HPSPS unit and maintain a reasonable maximum head to minimum head ratio to ensure the safe and stable operation of the unit. The current recommended approach is to use the unit in the low waterhead section to only pumping but not generating. The Schematic diagram of operating conditions of Lianghekou HPSPS unit in different head sections is shown in Fig.1.

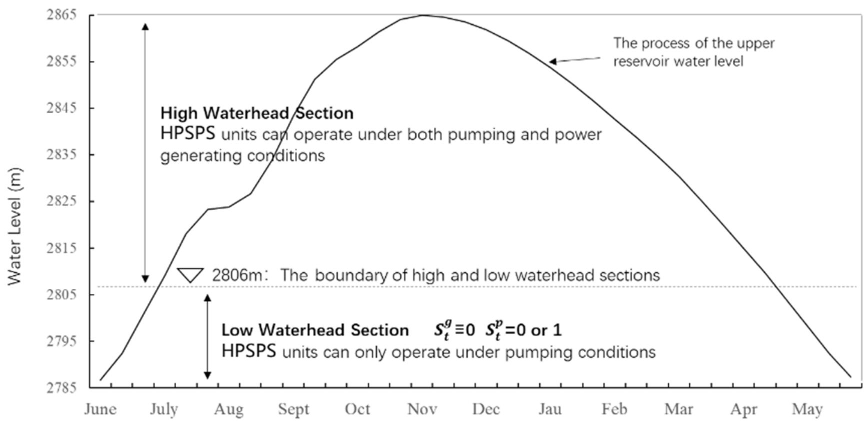

Fig. 1. Schematic diagram of operating conditions of Lianghekou HPSPS unit in different head sections

Objective Function. The scheduling of Lianghekou and the HPSPS must account for peak-shaving demands of the power system and integrated hydro-wind-solar operations. (1) With the integration of large-scale renewable energy into the grid, the midday peak has become a load valley, while peak-shaving demand remains high during the evening. Both Lianghekou hydropower station and the HPSPS offer excellent regulation performance, serving as key peak-shaving resources in the Sichuan grid. Maximizing their peak-shaving capacity is one of their primary operational objectives. Based on a simplified residual load profile, the peak-shaving power generation during the evening peak period from 19:00 to 23:00 is set as the objective function. (2) Given the abundant wind and solar resources around the Lianghekou hydropower station, both Lianghekou and the HPSPS are tasked with promoting renewable energy integration. During midday peaks, they leverage reservoir regulation and storage capabilities to balance the output, simultaneously reducing output to allow room for photovoltaic power integration while using excess photovoltaic output for pumped storage. This approach minimizes wind and solar curtailment and increases overall generation. Therefore, the integrated annual generation is also an objective function representing the HPSPS's role in complementing renewable energy.

Maximize Annual Peak-Shaving Power Generation

$$\max \sum_{i=1}^{365} \int_{t_1}^{t_2} \left[P(i,t) + N(i,t) + Y(i,t) \right] dt$$

Maximize Annual Power Generation

$$\max \sum_{i=1}^{365} \int_{1}^{24} \left[P(i,t) + N(i,t) + Y(i,t) + S(i,t) + W(i,t) \right] dt$$

where $P(i,t)$ $N(i,t)$ $Y(i,t)$,$S(i,t)$,and $W(i,t)$ represent the output of the Lianghekou hydropower station, Lianghekou HPSPS, Yagenyiji hydropower station, photovoltaic, and wind power at time t of day i (in MW);$t1$ and $t2$ are the start and end times of the peak-shaving period (in hours).

Constraints. Model constraints include water balance constraints, discharge flow constraints, expected output constraints, energy conversion constraints, etc. The detailed constraints are as follows.

(1) Hydropower Stations. he following constraints apply to the upper and lower reservoirs that constitute the HPSPS.

① Water Balance Constraint

$$V_{i,t} = V_{i,t-1} + (I_{i,t-1} \text{-} Q_{i,t-1}) \cdot \Delta t$$

Where $V_{i,t}$ and $V_{i,t-1}$are the storage volumes of the i-th hydropower station at time t-1 and t, respectively. And $I_{i,t-1}$and $Q_{i,t-1}$ are the inflow and outflow rates of the reservoir at time t-1, respectively, and Δt represents the duration of the time interval.

② Water Level Constraint

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

Where $Z_{i,t}$ is the water level of the i-th hydropower station at time t, and $Z_{i,t}^{min}$ and $Z_{i,t}^{min}$ are the minimum and maximum water levels of the reservoir at time t, respectively.

③ Discharge Flow Constraint

$$Q_{i}^{\min} \le Q_{i,t} \le Q_{i}^{\max}$$

Where $Q_{i,t}$ is the outflow rate of the i-th hydropower station at time t, and Q_i^{min} and Q_i^{max} represent the minimum outflow requirement and the maximum design discharge for power generation, respectively.

④ Power Output Constraint

$$N_{i}^{\min} \le N_{i,t} \le N_{i}^{\exp}$$

Where $N_{i,t}$ is the power output of the i-th hydropower station at time t, N_i^{min} is the minimum power output, and N_i^{exp} is the expected output under the current water head at time t.

⑤ Cascade Hydraulic Connection Constraint

$$Q_{i+1,t}^{in} = Q_{i,t}^{out} + Q_{i,t}^{l}$$

Where $Q_{i+1,t}^{in}$ is the inflow rate of the i+1-th hydropower station at time t, $Q_{i,t}^{out}$ is the outflow rate of the i-th hydropower station at time t, and $Q_{i,t}^{l}$ represents the interval flow between the i-th and i+1-th stations at time t.

(2) HPSPS.

① Output State Constraint

$$S_t^p + S_t^g \le 1 \quad (S_t^p, S_t^g \in \{0,1\})$$

Where S_i^p and S_i^g are the pumping and generating states of the HPSPS at time t, respectively. Both states can be 0 simultaneously but cannot be 1 simultaneously. It should be noted that in the low head section (below 2806m), the value of S_i^p can only be 0. This constraint condition helps the model adapt to the operation mode of HPSPS in different waterhead sections

② Energy Conversion Efficiency

$$G(T+1) = \beta \times P(T)$$

Where $\mathrm{G(T+1)}$ is the electricity generated by the HPSPS during period T+1, $\mathrm{P(T)}$ is the pumping energy during period T, and β is the energy conversion coefficient.

③ Continuous Full-Load Hours

$$G(T) / P \le T$$

Where $\mathrm{G(T)}$ is the electricity generated by the HPSPS during period T, P is the installed capacity of the station, and T represents the full-load operating hours.

Model Solution Approach. The construction of the HPSPS does not interfere with the annual regulation operations of the Lianghekou conventional station. The upper reservoir completes a cycle of drawdown, filling, and drawdown within a hydrological year. Starting with the monthly power scheduling process for Lianghekou as the initial value, the day-ahead scheduling of the upper reservoir is optimized according to the objective functions, with the principle of avoiding additional water spillage due to renewable energy integration. The lower reservoir is constrained by the fluctuation limits of downstream water levels, and the day-ahead power scheduling process is iteratively calculated based on the inflow to the upstream reservoir. The above model is solved using genetic algorithm.

2.2 Study on Operation Modes of Lianghekou and Lianghekou HPSPS

Based on the previously discussed characteristics of Lianghekou HPSPS, its operation is constrained by the characteristics of its turbine type. When the reservoir level is below 2806 meters (April to July each year), the water stored by the HPSPS through surplus wind and solar power cannot be directly discharged by the hybrid units and can only be released through the conventional units if available. Therefore, the operational modes of the HPSPS differ between low and high waterhead sections, as detailed below based on model calculations.

Operation Mode in Low Waterhead Section (Below 2806 m). In the low waterhead section, the power generation capability of the Lianghekou hybrid units can be replaced by the conventional units in two main modes: intra-day replacement when there is sufficient spare capacity in the conventional units, and cross-week replacement when there is no spare capacity.

Intra-Day Replacement: When inflows are average or below average from April to July, the conventional units at Lianghekou operate at low output levels with high spare capacity, enabling the conventional units to release all the pumped storage water, balancing intra-day pumping and generation.

Cross-Week Replacement: When inflows are above average from April to July, the output of the conventional units increases, and after balancing wind and solar power during the day, the evening peak output may already reach target levels. In this case, the stored water from the HPSPS's pumping cannot be fully discharged within the same day through the conventional units, but pumping can continue, storing the water for release in subsequent days when spare capacity is available.

A typical operation process of the combined generation of Lianghekou and Lianghekou HPSPS in the low waterhead section is shown in Figure 2.

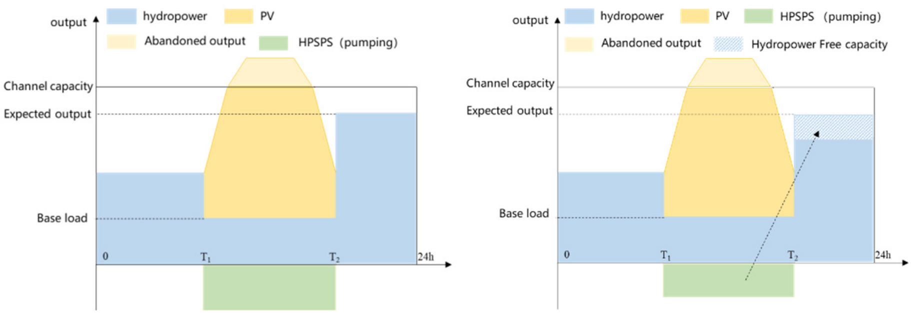

Fig. 2. Schematic diagram of combined operation of Lianghekou and Lianghekou HPSPS at Low waterhead section

Operation Mode in Medium to High Waterhead Section (Above 2806 m). In the medium to high waterhead section (August to March of the following year), the HPSPS's pumping and generating functions can operate normally, effectively increasing the installed capacity of the Lianghekou power station and enabling more flexible scheduling. Depending on the output of conventional units and renewable energy, the following operation modes are applied:

Generation Only: When photovoltaic output is relatively low during the midday peak, and no excess electricity is available, the hybrid units do not pump but instead generate power during the evening peak, utilizing stored water.

During the flood season, when the inflow to the Lianghekou reservoir is high and conventional units are fully generating but still unable to accommodate photovoltaic output, the HPSPS uses reservoir discharge to increase generation instead of pumping.

Pumping and Generation: When the conventional units are generating without any excess water, and the transmission corridor can accommodate most of the photovoltaic output, with curtailment only during peak hours, the HPSPS pumps water during the day and generates power in the evening, when there is transmission capacity available.

When the conventional units are fully generating without excess water, the HPSPS pumps water using surplus photovoltaic output at midday and generates power during the evening peak when the transmission corridor has spare capacity.

A typical operation process of the combined generation of Lianghekou and Lianghekou HPSPS in the high waterhead section is shown in Figure 3.

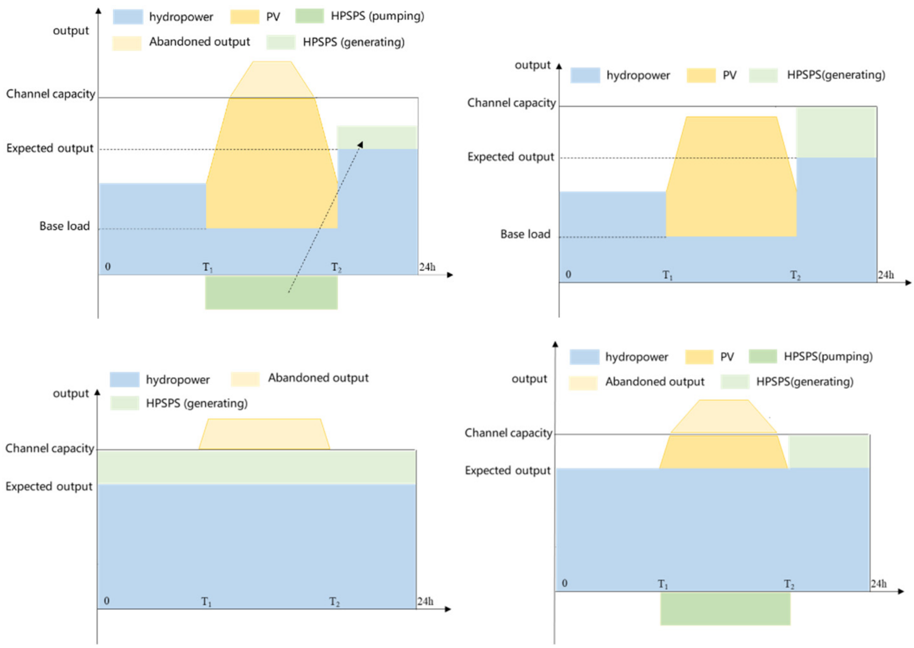

Fig. 3. Schematic diagram of combined operation of Lianghekou and Lianghekou HPSPS at high waterhead section

2.3 Operation Mode Study for Yagenyiji Station

The Yagenyiji station, acting as the reverse regulation reservoir for the Lianghekou power station and the lower reservoir for the Lianghekou HPSPS, must ensure adequate water supply during midday peak pumping while retaining enough storage capacity during evening peak generation to accommodate surplus water and minimize spillage. Additionally, it must control daily discharge fluctuations to maintain stable downstream water levels. Simulation results indicate that the daily water level cycle at Yagenyiji follows a "fill, drawdown, and refill" pattern, forming a "Z-shaped" daily water level curve. Figure 4 presents a typical daily operation process for Yagenyiji reservoir.

Simulation results reveal that HPSPS operation increases the drawdown depth of the Yagenyiji lower reservoir, reducing the average annual water level by approximately 0.4 m and significantly increasing the frequency of drawdown to dead storage level, with over 300 days on average reaching dead storage. Fig3 compares average water levels and drawdown frequency under different hydrological conditions.

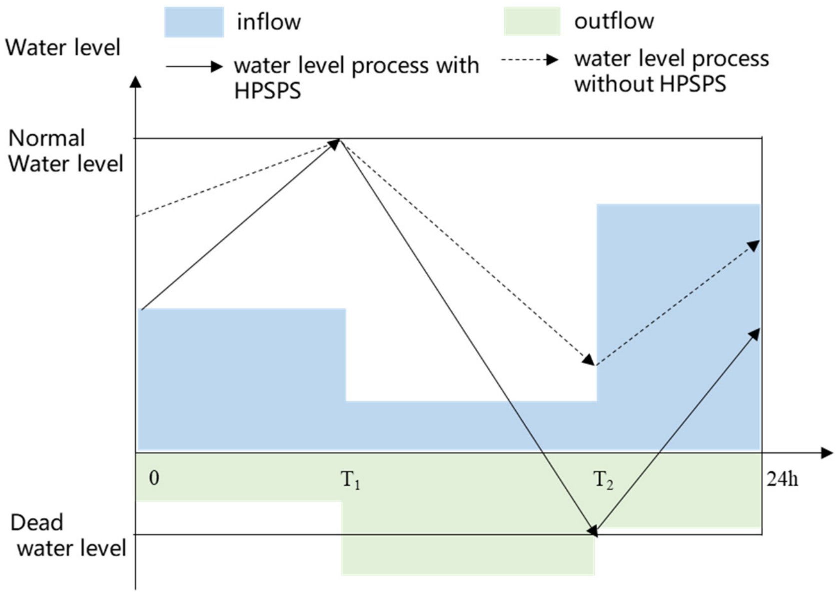

Fig. 4. Typical daily operation process of the Yagenyiji reservoir

2.4 Summary of Operation Modes for Lianghekou HPSPS

While the power generation capacity of hybrid units is limited in the low waterhead section, leading to differences in operation modes across various waterhead sections and diverse combinations under different boundary conditions, the overall operation mode of the two-reservoir, three-station system exhibits certain regularities, summarized as follows in Table 1.

Table 1. Operation mode of two reservoirs and three power stations

Station	Early Morning & Nighttime Valley	Midday Peak	Evening Peak
Lianghekou	Reduced Output	Reduced to Baseload for Wind & Solar Complementation	Peak-Shaving Generation
HPSPS	Not Operational or Low Output	Uses Surplus Wind & Solar for Pumping	Peak-Shaving Generation
Yagenyiji	LowOutput, Reservoir Filling	Reduced Output, Rapid Drawdown	Synchronizes with Peak Generation, Reservoir Refilling

3 Conclusion

This study investigates the operational characteristics of the Lianghekou HPSPS and develops a daily scheduling model. By analyzing the model's calculation results, daily scheduling strategies for the Lianghekou hydropower station, the Lianghekou HPSPS, and the Yagenyiji hydropower station are identified and refined, resulting in a relatively stable cascade-coordinated operation framework:

1. Low Head Section: The HPSPS absorbs surplus renewable energy through water pumping, replacing conventional units for power generation tasks.

2. High Head Section: A combination of conventional units and HPSPS units is employed to further enhance the cascade system's power generation capacity based on the inflow and new energy output.

3. Yagenyiji hydropower station Adaptation: The Yagenyiji hydropower station adapts to the daily scheduling of the HPSPS by increasing the depth of subsidence, facilitating coordinated operation between the upper and lower reservoirs.

The above scheduling operation strategies provide valuable guidance for the coordinated operation of two reservoirs and three stations, including HPSPS.

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