

Study on Optimal Operation of Hydropower Station Group Based on New Electricity Reform and Deviation Assessment

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Abstract. The new electricity system reform has brought power generation companies into the market, and the scheduling target of cascade hydropower stations has been transformed from maximizing power generation to maximizing revenue. Market rules require hydropower generators to pay assessment fees for the power generation deviation. Therefore, in order to obtain the desired revenue, power generators should not only obtain more power generation indicators and higher power prices, but also control the power generation deviation and avoid being assessed. In response to the current market environment, the new requirements of the new electricity system reform for hydropower scheduling were analyzed. And based on regional market rules, a scheduling model for cascade hydropower stations with the goal of minimizing generation deviation was established, taking the example of eight cascade hydropower stations in the downstream of Dadu River in Sichuan province as an example, the effectiveness and applicability of the model were verified. The results show that the deviation in each period can be controlled within 1% and meet the basic requirements of market rules.

1 Introduction

1.1 Research significance

Before the new electricity system reform, the hydroelectricity on-grid tariff was priced by the government. Therefore, according to the principle of fully utilizing the water resources in the basin, the aim of the model are always maximizing cascade power generation^[1-3] and minimizing water consumption^[4-6] in the traditional scheduling of cascade hydropower stations. The new electricity system reform will implement the policy of the non-profit public offering price formed by the market step-by-step. Hydropower generators acquire power generation indicators and electricity prices by participating in the electricity market, thus facing double risks of electricity quantity and prices. Under the market environment, the scheduling target of cascade hydropower stations has transformed into maximizing the revenue of power generation^[7].

The concept of deviation power was proposed in the document "Basic Rules for Mid-Long Term Trading (Provisional)". Since the contracted electricity in power contracts are all planned values, deviations between the actual electricity generation and the contract electricity are inevitable. The "Basic Rules" stipulates that power generation companies need to pay for the deviation (over- or under-sufficiency) electricity charges.

Therefore, under the current market rules, generators of cascade hydropower stations should not only obtain more power generation indicators and higher electricity prices, but also do a good job of controlling deviations to avoid being assessed in order to obtain maximum revenue. So it is very necessary to carry out scheduling research in conjunction with specific market rules. Creatively combining regional market rules, based on the criteria of full utilization of resources and minimization of cascade deviations in the river basin, a novel optimal operation model for hydropower stations with new electricity system reform has been established in this paper. And taking the example of eight cascade hydropower stations in the downstream of Dadu River in Sichuan province as an example, the effectiveness and applicability of the model were verified.

1.2 Literature review

The world power industry has gone through three stages (as shown in Table 1). After more than 100 years of reform, the power market has gradually evolved from a regional small-scale monopoly submarket to a large-scale freely competitive one^[8]. Since the 1990s, in accordance with the general laws of the market economy and the power industry, the government relaxed power control^[9], introduced free competition, and the deregulated electricity market gradually formed a real market. It has been more than 30 years for the

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construction of foreign power market, and developed countries such as the United States ^[10], the United Kingdom ^[11], and Australia ^[12] have established a relatively mature spot power market. The California market is a 15-minute market, and in the UK and Australian markets, power companies quote every 30 minutes and every 5 minutes, respectively. The ultra-short-term quotation of the spot market has brought tremendous pressure on the real-time dispatching of power plants. In particular, hydropower plants are faced with the risks of runoff uncertainty and water stagnation.

Table 1. World electricity market development process

Stage	Time	Market characters
1	Late 19th century to 1930s	Divided into sub-markets by city or region, power producers in submarkets conduct monopoly operations, and the government begins to introduce competition for regulation.
2	The 1940s to the end of the 1980s	Implementing regulation and vertical integration of monopoly on price and market access in the power industry, and maintaining its monopoly position by the government
3	The early 1990s to the present	Implement market-oriented reforms to introduce market competition through vertical and horizontal cutting, recognizing that power resources can be effectively deployed through the market.

In foreign countries, due to the development of the spot market, the optimal scheduling of hydropower stations is mainly focused on short-term scheduling. Spanish scholars Pérez-Díaz J I et al. established a dynamic programming model^[13] and presented a novel approach^[14] to solve the short-term operation scheduling problem of a hydropower plant that sells energy in a deregulated electricity market with the objective of maximizing its revenue. In 2016, Bello S A et al.^[15] presented a new formulation and classical exhaustive enumeration search method for the well-known unit commitment problem for scheduling thermal and hydroelectric power generating units in a day-ahead electricity market. In Ref.16, considering daily operation in hourly interval, the authors proposed a new method for optimal self-scheduling of cascaded hydro power plants in energy and reserve electricity markets, which has been applied to a cascaded system with three hydropower plants over a time horizon of 24-hours.

Some domestic scholars in the industry have also studied that how do generation companies get the most benefits in the face of the dual uncertainty of electricity and prices. Liu Fang, Zhang Lizi et al. at North China Electric Power University have done a lot of research, and successively proposed mid-long term models for cascade hydropower stations, such as bi-level optimal model of scheduling and maintenance planning^[17], optimization model of scheduling transaction considering stochastic and risk factors^[18] and bi-level

optimization model for scheduling and cross-price area trading portfolio^[19]. The maintenance plan, transaction combination, electricity price volatility, and runoff randomness were separately introduced into these models in order to obtain the maximum power generation revenue. The authors introduced the abundant-dry water price into the revenue maximization model, and studied the optimal scheduling of single power station in Ref. 20. Taking other bidder's competitive behaviors, electricity load demand and market price into consideration, a new model^[21] for optimal operation of cascade hydropower plants in deregulated electricity market was proposed. In Ref. 22, the characteristics of the optimal reservoir scheduling in the electric power market transaction model were analyzed, and the optimal operation model of the reservoir was established.

2 New requirements for hydropower scheduling

In the past, the on-grid tariff was mainly based on government pricing. The new electricity system reform changed this pricing method. Now, the on-grid tariff of power generation companies participating in the power market transaction is determined by the user or the power selling entity and the power generation enterprise through negotiation and market bidding. Under the market rules, hydropower generators face great opportunities, but at the same time, they also face enormous challenges. Therefore, the new electricity system reform has put forward some new requirements for the schedule of hydropower.

(1)Reduce water consumption rate of power generation and optimize economic performance indicators. The new electricity system reform has introduced competition on the power generation side, and hydropower companies are under tremendous pressure. The power generators should first optimize the indicators for economic operation, reduce the cost of power generation, increase the profitability and the amount of power generation, so as to increase the income from power generation. During the flood season, load of generator sets should be kept as high as possible; while during the dry season, the reservoir water level should be operated as high as possible. At the same time, the unit's annual operating load rate should be increased as much as possible, and as far as possible, the unit's no-load and low-efficiency zone operating time should be avoided and reduced to increase power generation.

(2)Actively adjust quantity-price structure and make more expensive electricity. Under the new electricity system reform, hydropower continues to implement the policy of abundant-dry water price. Therefore, the company should actively adjust the price structure in light of actual conditions, make full use of the capacity of reservoirs to seize high-priced electricity, and optimize the pricing strategy to ensure maximum efficiency of power generation. At the same time, scientifically arrange impoundment and discharge order

of the reservoir to achieve long-term income-generating and efficiency-enhancing purposes.

(3) Give full play to advantages of the leading reservoir and achieve unified scheduling at cascades. On the one hand, the unified scheduling of river basins can give full play to the impoundment and regulation of the leading reservoirs, and the cascade water resources in the river basin can be optimized to the maximum extent to maximize the comprehensive benefits of the river basin. On the other hand, power generation companies jointly participating in the market making the relationship between stations transfer from competition to cooperation. It is possible to obtain additional revenue by optimizing load distribution and to maximize the profits of cascade power production in the river basin.

(4) Change the traditional production management model and guide the production with the market. Under the new electricity system reform, the schedule of hydropower stations is no longer a purely “water-based electricity” model. Under the premise of meeting other comprehensive utilization tasks of the reservoir, power generation companies should closely integrate market rules and rationally arrange the unit maintenance plan and generate electricity in accordance with the contract to avoid deviation assessment to obtain the expected return.

(5) Actively carry out water and electricity joint scheduling to deal with electricity price real-time trading. The promotion of new electricity system reform will promote the formation of a real-time bidding system for power trading. Based on real-time hydrological information and market dynamics information, power generation companies should adopt a combination of water and electricity adjustments, and carry out real-time hydropower scheduling to deal with real-time transactions.

3 Model establishment

According to the criteria for the full use of water resources, a trading strategy for cascade power stations to participate in the market as a coalition body is proposed in the paper. Under this strategy, we established a optimal scheduling model for hydropower stations under the new electricity system reform, and achieved the optimal allocation of contract power for each station within coalition. The model is solved using dynamic programming.

3.1 Objective function

The objective function of the model is minimizing the deviation of cascade stations between practical generating volume and contract power generation to get the most earnings.

$$\min \sum_{t=1}^T \left(\sum_{i=1}^N A_i \cdot Q_{i,t} \cdot H_{i,t} \cdot \Delta t - P_t \right)^2 \quad (1)$$

$$P_t = m_t + f_t \quad (2)$$

$$m_t = m_{1,t} + m_{2,t} + \dots + m_{n,t} \quad (3)$$

Where i is plant variables, N is total number of

cascade power stations, t is period variables, T is total number of calculation period during the year, in the contracts $T=1,2,\dots,12$ (Monthly contract) or $T=1,2,\dots,36$ (Ten-day contract). A_i is the efficiency coefficient of station i , $Q_{i,t}$ (m³/sec) is the power discharge of station i at time t , $H_{i,t}$ (m) is the net head of station i at time t , Δt is hours of every period, P_t (kW·h) is total contract power of cascade stations, f_t (kW·h) is inter-provincial transaction power of cascade stations, which is carried out on the Beijing trading platform, using listed trading methods, m_t (kW·h) is transaction power of cascade stations inside the province, possibly including electricity of direct power trading, excess power increase transaction, residential life energy replacement purchase transaction during the flood season, auxiliary service transaction, power generation side contract power transfer transaction, deviation power adjustment transaction, etc. $m_{i,t}$ is the transaction volume of various types of trading, and n is number of power trading varieties inside the province, determined by actual transaction.

3.2 Restrictions

(1) Water balance

$$V_{i,t+1} = V_{i,t} + (R_{i,t} - Q_{i,t} - S_{i,t})\Delta t \times 3600 \quad t \in T \quad (4)$$

Where $V_{i,t+1}$ (m³) is the reservoir capacity of the hydropower station i at the end of time t , $V_{i,t}$ (m³) is the reservoir capacity of the hydropower station i at the beginning of time t , $R_{i,t}$ (m³/sec) is the inflow of station i at time t , $S_{i,t}$ (m³/sec) is the abandoned water flow of station i at time t . The meanings of the other parameters are as above.

(2) Reservoir pondage

$$V_{i,t}^{\min} \leq V_{i,t} \leq V_{i,t}^{\max} \quad \forall t \in T \quad (5)$$

Where $V_{i,t}^{\min}$ (m³) is the reservoir's minimum pondage of station i at time t , $V_{i,t}^{\max}$ (m³) is the reservoir's maximum pondage of station i at time t , which is usually based on safety considerations of the reservoir, such as flood control restrictions during the flood season. The meanings of the other parameters are as above.

(3) Reservoir outflow

$$Q_{i,t}^{\min} \leq (Q_{i,t} + S_{i,t}) \leq Q_{i,t}^{\max} \quad \forall t \in T \quad (6)$$

Where $Q_{i,t}^{\min}$ (m³/sec), $Q_{i,t}^{\max}$ (m³/sec) are respectively the minimum and maximum outflow of station i at time t . The meanings of the other parameters are as above.

(4) Output of power station

$$N_{i,t}^{\min} \leq N_{i,t} \leq N_{i,t}^{\max} \quad \forall t \in T \quad (7)$$

Where $N_{i,t}^{\min}$ (kW), $N_{i,t}^{\max}$ (kW) are the minimum and maximum output of station i at time t , respectively, $N_{i,t}$ (kW) is the output of station i at time t .

(5) Water connections between cascade hydropower stations

$$R_{i,t} = Q_{i-1,t-1} + S_{i-1,t-1} + I_{i,t} \quad (8)$$

Where $Q_{i-1,t-1}$ (m³/sec) is the power discharge of station $i-1$ at time $t-1$, $S_{i-1,t-1}$ (m³/sec) is the abandoned water flow of station $i-1$ at time $t-1$, $I_{i,t}$ (m³/sec) is the interzone inflow at time t between station i and $i-1$. The meanings of the other parameters are as above.

(6) Non-negative conditions

Variables all the above are non-negative.

4 Case study

4.1 Regional electricity market rules

Under the market conditions, as far as the power producers are concerned, there is bound to be a deviation between the contracted electricity and the actual power generation. In order to reduce the deviation, the power generators can participate in the up or down adjustment services. The document "Guidelines for Sichuan Power Trading in 2018" pointed out that the increase and reduction in power generation caused by the participation in the up and down adjustment services are settled based on the prices of the pre-listing of the unit. The reduction of power generation is less than 2%, there's no compensation fees, while the reduction exceeds 2%, the compensation is paid in full. As for reduction, less than 2% is free from paying the cost of deviation assessment, greater than or equal to 2%, the power generation company have to pay the deviation assessment fees according to compensation price of upload adjustment service. In the abandoned water period, the increase of power generation will not be settled, within 2% of which will be exempted from payment of the deviation assessment fees, and greater than or equal to 2% will be paid by 10% of the highest price of monthly or weekly incremental direct transaction as deviation assessment fees. During the non-abandoned water period, the increase of power generation will be settled at 60 yuan/MWh.

Therefore, as we can see from the trading rules, in order to obtain the expected revenue, power generation companies must arrange power generation and production according to the power generation contract, control the power generation deviation within 2%, and avoid paying deviation assessment fees.

4.2 Overview of cascade power stations

Table 3. Water level and discharge process of Pubugou reservoir

Time	Water level at the end of the time(m)	Inflow(m ³ /s)	Power discharge(m ³ /s)	Abandoned water flow(m ³ /s)
Early January	843.64	508	765	0
Mid-January	840.18	456	772	0
Late January	835.7	427	787	0
Early February	831.06	400	795	0
Mid-February	825.8	373	801	0
Late February	821.36	382	815	0

The total installed capacity in production in the lower reaches of Dadu River is 8047MW, including 8 hydropower stations. Among them, the 6-level power stations from Pubugou to Tongjiezi were invested by Guodian Dadu River Hydropower Development Co., Ltd, while the last two stations Shengda and An'gu were invested and constructed by China Hydropower Construction Group Santa Fe Hydropower Co., Ltd. That is to say, it's a multi-owner joint development basin cascade. The Pubugou is a controlled reservoir power station in the downstream of the Dadu River, which has an incomplete annual regulating capacity, and the others are daily regulating power stations. The major parameters of Pubugou and the following cascade hydropower stations are shown in Table 2.

Table 2. Major parameters of Pubugou and the following cascade hydropower stations

Plant name	Installed capacity (MW)	Mean annual energy production (10 ⁸ kW·h)	Warranted output (MW)
Pubugou	3600	145.80	926
Shenxigou	660	32.35	253
Zhentouba level 1	720	32.90	206
Sha'ping level 2	345	16.10	124.5
Gongzui	770	34.18	179
Tongjiezi	700	32.36	137.7
Shengda	480	24.07	151
An'gu	772	31.44	203

4.3 Results and discussion

Taking Pubugou and the following cascade hydropower stations as an example, an optimal scheduling model driven by the market of cascade hydropower stations was established in this study and achieved optimal distribution in the year of contract power among the eight power stations. The model aims at minimizing the deviation between the power generation of the cascade power plant group and the contracted electricity, and is solved by a dynamic programming algorithm. Taking the design normal flow year 1956 as an example, a simulation calculation was conducted, and the results are as follows. Table 3 and Figure 1 show the water level and flow process of the reservoir and the output process of the cascade power stations, respectively.

Time	Water level at the end of the time(m)	Inflow(m³/s)	Power discharge(m³/s)	Abandoned water flow(m³/s)
Early March	815.68	397	823	0
Mid-March	809.54	410	842	0
Late March	803.02	468	853	0
Early April	797.46	530	865	0
Mid-April	792.26	593	881	0
Late April	790	766	884	0
Early May	791.48	950	873	0
Mid-May	795.48	1128	911	0
Late May	790	1468	1735	0
Early June	795.6	1869	1568	0
Mid-June	803.22	2139	1685	0
Late June	810.96	2189	1680	0
Early July	817.44	2149	1684	0
Mid-July	824.26	2199	1679	0
Late July	828.68	2099	1777	0
Early August	829.1	1999	1965	0
Mid-August	828.18	1899	1974	0
Late August	829.84	2089	1966	0
Early September	833.66	2279	1958	0
Mid-September	839.58	2469	1951	0
Late September	841.06	2099	1965	0
Early October	850	1819	982	0
Mid-October	850	1449	1449	0
Late October	850	1289	1289	0
Early November	846.84	1150	1452	0
Mid-November	849.52	992	737	0
Late November	849.98	867	823	0
Early December	850	758	756	0
Mid-December	848.68	620	747	0
Late December	846.4	560	757	0

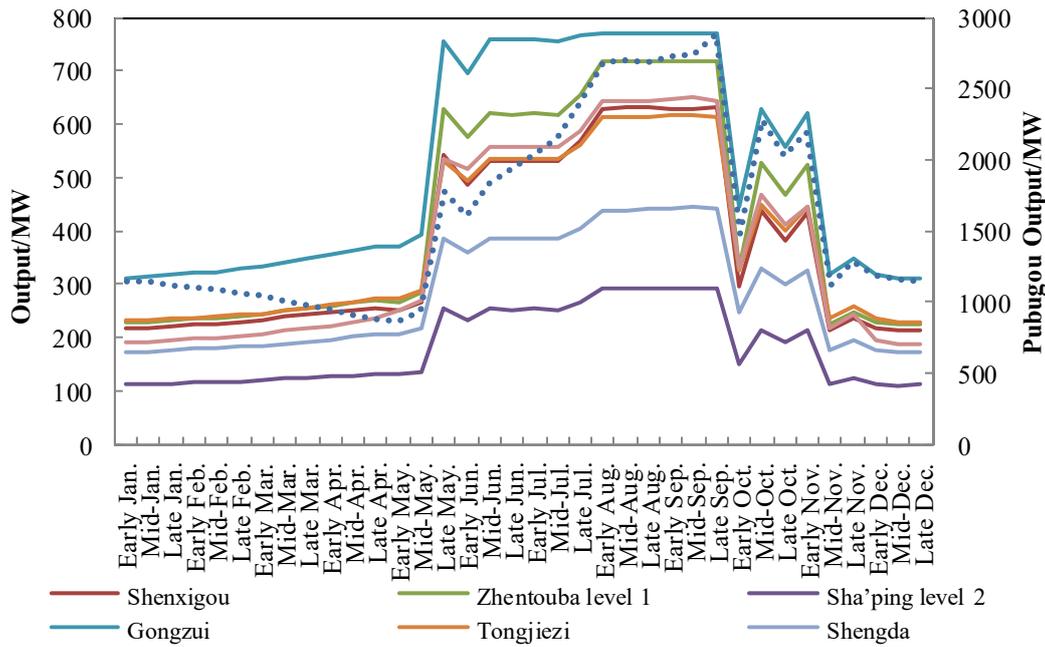


Figure 1. Output process of cascade hydropower stations

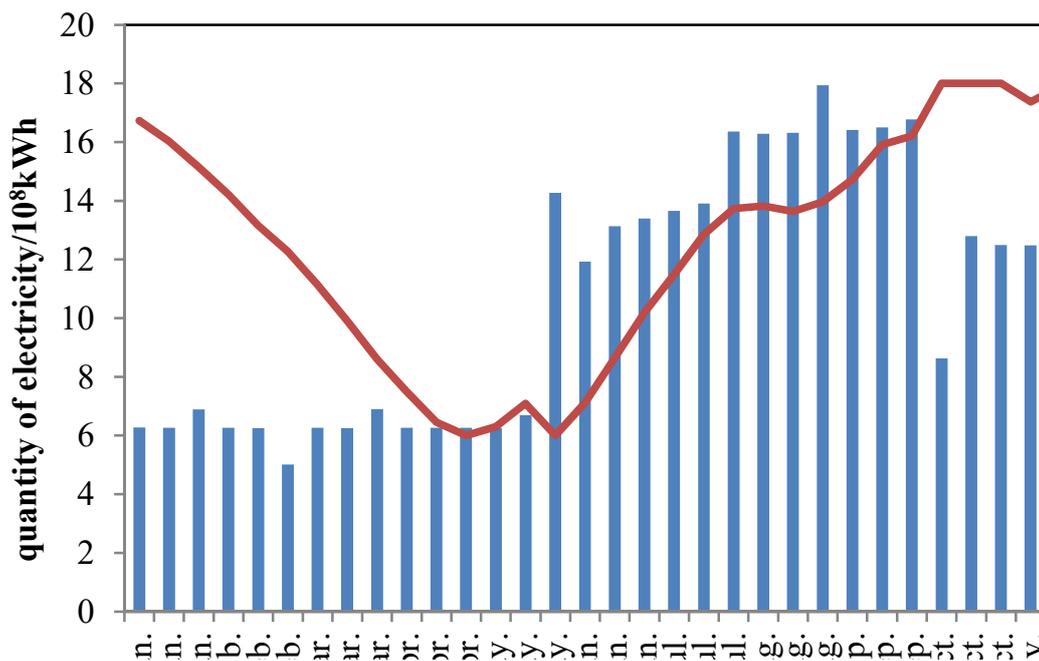


Figure 2. Water Level Process of Pubugou Reservoir and Cascade Electricity process

Judging from criterion for the full use of resources: influenced by the reservoir regulation capacity and incoming water, the water level of the Pubugou reservoir fell to the dead water level of 790m in late April (the end of the dry season) and late May (the beginning of the flood season), and the reservoir was filled up in Early October. The water level was maintained at 850 meters throughout October, maintaining a high head for the dry period and meeting the requirements of the reservoir's operation mode. No water of Pubugou reservoir was abandoned at all times, that is to say, the water utilization rate was as high as 100%, and the water

resources were used efficiently. Through optimization calculation, the output process of each station in the cascade is shown in Figure 1. Except for the leading reservoir Pubugou, the output process of the other seven power stations has great similarity, the minimum output all occurs in mid-December, while the minimum output of Pubugou is in early May. The warranted output of the whole cascade increased from 2180.2MW to 2626MW, making an increase of 20.45%. Compared with the mean annual energy production, optimized annual power generation of the cascade increased by 1.507 billion kW·h, making an increase of 4.32%. The optimized

scheduling plan has a significant increase in power generation, effectively increasing the power generation benefit of the reservoir. The Pubugou water level process and cascade electricity process are shown in Figure 2.

The optimal scheduling model under the new electricity system reform established in chapter 3 was used to optimize the power generation process of Pubugou and the following cascade power stations. The actual power generation, contracted electricity process, and power generation offsets of the cascade power stations are shown in Table 4. Except in late December, the absolute values of the power generation deviation in each ten days (the ratio of the absolute value of the power deviation to the contracted power) are all within 1%. Over the process of the year, there is a trend of "super-dry season with shortfall in flood season", and the

negative deviations are slightly larger than the positive deviations. The maximum negative deviation occurred in late December, which was -1.02%, and the maximum positive deviation appeared in early June, which was 0.09%. Monthly deviations can all be controlled within 1%, with a minimum deviation of 0.01% in September and a maximum of 0.97% in December. According to the relevant provisions of the "Guidelines for Sichuan Power Trading in 2018", deviations within 2% are exempt from payment of deviation assessment fees.

Judging from the overall deviations during the year, the cascade hydropower stations participating in the power market as a coalition body, on the one hand, can make full use of water resources and avoid water abandonment, on the other hand, can better balance deviations and avoid paying assessment fees.

Table 4. Power generation deviations at each time of the cascade hydropower stations

Time	Actual generation(10 ⁸ kW·h)	Contract power(10 ⁸ kW·h)	Deviation of power(10 ⁸ kW·h)	Ten-day deviation	Monthly deviation
Early January	6.27	6.30	-0.04	-0.60%	-0.60%
Mid-January	6.27	6.30	-0.03	-0.51%	
Late January	6.89	6.93	-0.05	-0.67%	
Early February	6.27	6.30	-0.03	-0.55%	-0.64%
Mid-February	6.26	6.30	-0.04	-0.68%	
Late February	5.01	5.04	-0.03	-0.68%	
Early March	6.26	6.30	-0.04	-0.61%	-0.62%
Mid-March	6.26	6.30	-0.04	-0.64%	
Late March	6.89	6.93	-0.04	-0.62%	
Early April	6.27	6.30	-0.04	-0.57%	-0.57%
Mid-April	6.27	6.30	-0.03	-0.55%	
Late April	6.27	6.30	-0.04	-0.57%	
Early May	6.27	6.30	-0.04	-0.57%	-0.38%
Mid-May	6.70	6.73	-0.04	-0.53%	
Late May	14.28	14.32	-0.03	-0.23%	
Early June	11.92	11.91	0.01	0.09%	0.06%
Mid-June	13.14	13.14	0.00	0.03%	
Late June	13.39	13.38	0.01	0.05%	
Early July	13.66	13.65	0.01	0.08%	0.04%
Mid-July	13.90	13.90	0.00	0.03%	
Late July	16.36	16.36	0.00	0.01%	
Early August	16.29	16.28	0.01	0.07%	0.04%
Mid-August	16.32	16.32	0.01	0.05%	
Late August	17.95	17.95	0.00	0.02%	
Early September	16.42	16.42	0.00	0.01%	0.01%
Mid-September	16.49	16.49	0.00	0.01%	
Late September	16.77	16.77	0.00	0.02%	
Early October	8.63	8.63	0.01	0.06%	-0.19%
Mid-October	12.80	12.83	-0.03	-0.22%	
Late October	12.50	12.54	-0.04	-0.31%	

Time	Actual generation(10 ⁸ kW·h)	Contract power(10 ⁸ kW·h)	Deviation of power(10 ⁸ kW·h)	Ten-day deviation	Monthly deviation
Early November	12.50	12.53	-0.03	-0.26%	-0.38%
Mid-November	6.27	6.30	-0.03	-0.52%	
Late November	7.05	7.08	-0.03	-0.48%	
Early December	6.40	6.46	-0.06	-0.92%	-0.97%
Mid-December	6.24	6.30	-0.06	-0.96%	
Late December	6.86	6.93	-0.07	-1.02%	

5 Conclusions and prospect

The new electricity system reform has brought power generation companies into market competition. Hydropower as a kind of clean and renewable energy source has certain advantages, but it also faces a series of challenges. In this paper we analyzed the new requirements of the new electricity system reform for hydropower scheduling, based on which, a optimal scheduling model of hydropower station group was established. Taking the Pubugou reservoir of Dadu River in Sichuan Province and the following 7-stage power stations as an example, the validity and applicability of the model are verified. The main conclusions are as follows:

(1)Under the background of the new electricity system reform, the objective of the optimal scheduling of hydropower stations has been transformed from the maximization of power generation to the maximization of power generation revenues. Under the current market rules, in order to obtain maximum returns, hydropower companies should control power generation deviations in addition to obtaining as many power generation and as high electricity prices as possible.

(2)Hydropower companies should take more measures to obtain the expected benefits: firstly, reduce water consumption rate of power generation, optimize the economic operation indicators of the power station, actively adjust quantity-price structure to generate more high-priced electricity. Secondly, give full play to advantages of the leading reservoir and form a coalition of all cascade sations to participate in the market to achieve unified scheduling at cascades. Thirdly, change the traditional production management model, guide production through the market, and actively implement water and electricity joint scheduling to cope with real-time electricity price transactions.

(3)Taking one year as a calculation cycle and ten-day as a calculation period, the optimal scheduling model of the hydropower station group under the new electricity system reform was established, and the contract power allocation was carried out for Pubugou reservoir and the following 7-level power stations. The deviation of each month can be controlled within 1%, meeting the requirement of the document “Guidelines for Trading in Sichuan Power Market in 2018”, which is 2% , so power producers can be exempted from paying deviation assessment fees.

Based on specific regional electricity market rules, we proposed a scheduling model that minimizes generation deviation of cascade hydropower plants in this study, which is of guiding significance for the operation mode of cascade hydropower stations participating in the power market. In the future, with the opening of the spot market, real-time and rolling correction of deviations should be the focus and difficulty of scheduling at cascades in the market environment.

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