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Short-term hydro generation operation of cascade hydropower stations in Han River, China

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Abstract. Hydropower is a natural renewable energy with outstanding technological superiority in short-term operation. Short-term hydro generation operation (SHGO) requires not only lord dispatch in single station, but also the coordination of hydraulic and electric connection for different stations. In this paper, a coordinated peak shaving operation method of cascade hydropower stations is proposed. Firstly, regular pattern of peak load regulation is analyzed using the load characteristics of power grid. The daily power output of cascade hydropower stations should meet the needs of typical load pattern. In order to satisfy comprehensive utilizations of water resources, the outflow of each reservoir should be no less than the demand of water supply or irrigation. To verify the feasibility and effectiveness of the proposed method, an application of Pankou and Xiaoxuan cascade hydropower stations, located in Hanjiang River in China, is presented in this paper. Simulation results indicate that the proposed method can obtain the maximum peak shaving amplitudes and suggested peak shaving amplitudes at the same time, which satisfies different operation demands of cascade hydropower stations.

1. Introduction

The operation of cascade hydropower stations is an operation problem for more than one hydropower stations. The target of this problem is to improve waterpower utilization rate and power generation, while requirements of flood control, water supply and output of each hydropower station are satisfied[1]. The operation of cascade hydropower stations can be divided into three main categories: mid-long-term operation, short-term operation and real-time operation. As a short-term optimal operation problem of electric system, short-term hydro generation operation (SHGO) requires the coordination of different departments and multiple stations. Hydropower stations have to allocation water resources on the basis of the runoff and storage capacity of reservoir. On the other hand, power output generated by water resources should meet the requirement of power demand and grid management. Therefore, technical and managerial challenges remain to be solved for the coordination of these departments and water resources allocation in different stations.

The SHGO problem is a typical nonlinear mixed optimization problem is to figure out the daily power output, as well as the maximum amplitude of load shaving, which is determined by limited water resources and power demand. In the past few years, many studies on short-term scheduling operation mainly focused on the new energy construction, for example, developing pumped-hydro energy storage stations[2–4], gas-fired power stations[5–7] and energy storage[8,9], or optimization models and methods for peak shaving on the power grid side[10,11]. Other studies concentrate on algorithm and application of short-term hydro generation scheduling, such as particle swarm optimization[12,13], genetic algorithm[14], differential evolution[15], and the application of world largest hydropower plants, Three Gorges-Gezhouba cascade[16] and Xiluodu-Xiangjiaba cascade[17]. However, traditional short-term hydro generation scheduling aims to minimize the total water consumption while simultaneously meeting some hydraulic and electrical constraints. The requirement of power demand is ignored especially when the hydropower stations play a significant role in power grid. On the other hand, peak shaving capability of other new energy is limited by their distinguishing features and energy policy in China. Therefore, the research of SHGO problem is meaningful and crucial to enhance the waterpower utilization rate of the station and dependability of the power system.

In order to solve the SHGO problem, a method of peak shaving operation for cascade hydropower stations is proposed in this paper. Firstly, regular pattern of peak load regulation is analyzed using the system and load characteristics. The daily power output of cascade hydropower stations should meet the needs of typical load pattern. Then the comprehensive utilizations of each reservoir transfer into constraints which should be considerde. To verify the feasibility and effectiveness of the proposed method, an application of Pankou and Xiaoxuan cascade hydropower stations is presented for case study. Pankou and Xiaoxuan cascade hydropower stations are located along the Duhe River, which flows through Hubei Province in China and joins the Hanjiang River at about 127.2 km upstream of Danjiangkou Reservoir. Hanjiang River is the water source of Mid-Route of South-To-North Water Transfer Project, which is diverting water from Hanjiang River in middle of China to the north[18,19]. The project characteristics of Pankou and Xiaoxuan cascade hydropower stations are shown in Table 1.

Table 1 Project characteristics of Pankou and Xiaoxuan hydropower stations

Project	Pankou hydropower station	Xiaoxuan hydropower station
Basin area (km^2)	8950	9040
Normal pool level (m)	355	264
Flood control level (m)	347.6	264
Dead water level (m)	330	261.3
Total storage capacity (billion m^3)	2.34	0.04
Installed capacity (MW)	500	50
Number of units	2	3
Yearly average power output (billion kW•h)	1.05	0.15

Since Pankou and Xiaoxuan cascade hydropower stations are put into use, some concerns have been raised about the increasing conflict between short-term scheduling and high efficient utilization of water resources. In this study, we analyzed the load characteristics of Hubei provincial power grid and Siyan regional power grid that connected power from Pankou and Xiaoxuan hydropower stations in Hubei Province. So the typical load pattern of peak load regulation that cascade hydropower stations followed was proposed. Then, the coordinated peak load regulation of cascade hydropower stations is analyzed, which could provide some important support to the solution of SHGO problem.

2. Typical load pattern of peak shaving for cascade hydropower stations

In general, the power energy generated by Pankou and Xiaoxuan cascade hydropower stations is consumed primarily by local users in the northwest of Hubei Province. During the flood season from May to September, the power energy is consumed mainly by Shiyan city, and the surplus power is fed to Hubei power grid by a double-circuit 500kV line. Thus the typical load pattern of peak shaving that cascade hydropower station followed should consider the load characteristics of both Hubei provincial power grid and Siyan regional power grid.

2.1. Load characteristics of Hubei provincial power grid and Shiyan regional power grid

Hubei power grid is the passage of the West-to-East Electricity Transmission Project and the North-to-South Electricity Transmission Project[20,21] in China. Hubei power grid shows a double-peak curve of daily load. One peak is in the morning and a second peak in the evening. According to the daily load of Hubei power grid measured in recent years and the 12th “Five-year” Development Plan of

Hubei Power Grid[22], the typical maximum daily load of Hubei power grid is shown in Fig.1.Shiyan power grid is responsible for delivering the electrical energy to local users in Shiyan City. Similar to the Hubei power grid, a double-peak curve of daily load is observed for Shiyan power grid, with one peak in the morning and a second peak in the evening. A typical daily load curve of Shiyan regional power grid is shown in Fig.2.

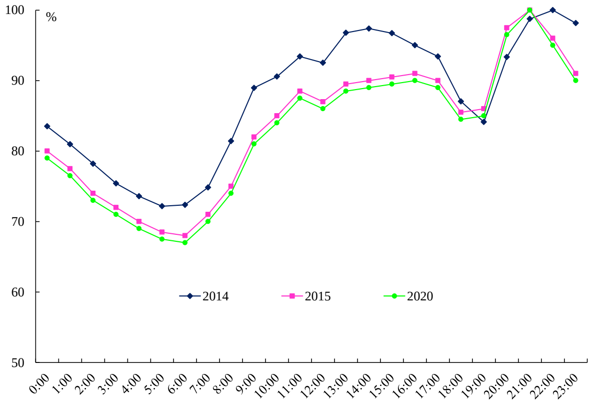

Figure.1 Typical dailwy load curve of Hubei power grid

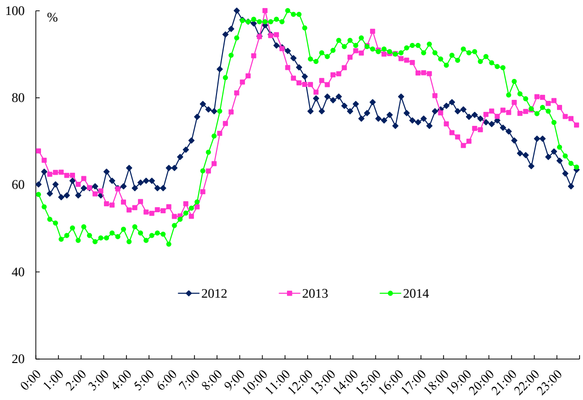

Figure.2 A typical load curve of Shiyan power grid

2.2. Load pattern of peak shaving for cascade hydropower stations

As it is estimated the daily load curve of both Hubei power grid and Shiyan power grid will remain largely unchanged for years to come. Considering that the evening peak of Hubei power grid occurs later than that of Shiyan power grid, two distinct regulation models should be adopted. We call them "Peak shaving model A"(Shiyan peak load regulation model) and "Peak shaving model B" (Hubei peak load regulation model). Therefore, the typical load pattern of peak shaving that cascade hydropower station followed can be figure out by the load characteristics of both Hubei provincial power grid and Siyan regional power grid.

2.2.1. Peak shaving model A Shiyan peak load regulation model. According to the peak-load characteristics of Shiyan power grid, two peak loads are observed at 8:00~12:00 and 14: 00~18: 00 during which peak-load regulation is required, and valley load lasts for at least 8 hours, typically from 23:00 to 7:00 of the next day. The rest of the day is usually governed by intermediate load.

2.2.2. Peak shaving model B: Hubei peak load regulation model. The peak load occurs at 8:00~12:00 in the morning and 18:00~22:00 in the evening, while the valley load occurs from 23:00 to 7:00 of the next day.

3. Coordinated peak shaving operation

The peak shaving operation of cascade hydropower stations, as the main model of short-term operation, depends mainly on the load characteristics of the power grid and the regulation capacity of the reservoir. The peak shaving operation of hydropower stations should be in accordance with the typical load pattern of power grids which stations supply. Therefore, the generalized procedures of coordinated peak shaving operation for the cascade hydropower stations can be expressed as follows:

Step 1: Read the started water level $\underline{Z}$ and average water discharge of one day Q by the result of by mid-long term operation of hydropower station.

Step 2: Calculate the average power generation of hydropower stations by the formula as follows. Set the intermediate load $L_{inter}=N_{avg}$, iteration coefficient i=1.

$$N_{avg} = \sum_{i=1}^{N} p_i = \sum_{i=1}^{N} 9.81 \bullet \eta \bullet q \bullet h \quad (1)$$

Where the p_i is the power generation of *i*th unit. η is the turbine-generator efficiency, which is indexed by the efficiency curve of the hydropower unit. q and h are the water discharge and effective water head, respectively.

Step 3: Use the typical load pattern of peak shaving extracted by the analysis of power grid to generate the daily output of hydropower stations. Calculate the peak-load and valley-load as follows:

$$L_{peak} = L_{inter} + \frac{N_{\max} - N_{\min}}{IC} \times i \quad , \quad L_{valley} = L_{inter} - \frac{N_{\max} - N_{\min}}{IC} \times i \tag{2}$$

Step 4: If $L_{peak} \geq N_{max}$ or $L_{valley} \leq N_{min}$, turn to **Step 7**; otherwise turn to **Step 5**.

Step 5: If total discharging water $W_d = \sum_{k=1}^{K} w_k > 0$, turn to **Step 7**; otherwise turn to **Step 6**.

Step 6: If $i = IC$ (the maximum of the iteration number) turn to **Step 7**; otherwise go back to **Step 2**.

Step 7: The search is terminated and output the solutions as the final results. Otherwise, set $i = i + 1$ and go back to **Step 2**.

4. Implement of coordinated peak shaving operation for SHGO problem

4.1. Coordinated peak shaving operation scheme

The purpose of Pankou and Xiaoxuan cascade hydropower stations are flood control, water supply and power generation. The tasks of flood control and water supply take precedence over power generation, as well as peak shaving operation. Therefore, considered the requirements of cascade hydropower stations for peak shaving, the scheme of coordinated peak shaving operation is proposed:

Case 1: If the power generating flow is small, cascade hydropower stations can take full responsibility for peak shaving operation on the premise that the water demand in the downstream area can be well satisfied;

Case 2: If the power generating flow is large, it is necessary to avoid abandoned water caused by peak load regulation. So peak shaving amplitude of upstream station should be limited. The maximum amplitude occurs when the water discharge of upstream station is just the full-load flow of downstream station;

Case 3: If the power generating flow is moderate, peak load regulation scheme should be selected prudentially to avoid radical scheme and to take into account the transition between different schemes.

4.2. Simulation results

In order to ensure a uniform discharge and avoid abandoned water as much as possible during the anti-regulation of Xiaoxuan hydropower station, it is necessary to restrict the peak shaving amplitude of Pankou hydropower station. In this way, the daily power generating flow can be determined. The full-load flow of Pankou hydropower station is 680 m^3/s, which is set as the upper limit of the power generating flow. As mentioned above, the water supply of downstream is the requirement of water supply in peak shaving. Thus an important constraint for the peak shaving operation of Pankou hydropower station is that the minimum discharge of Xiaoxuan hydropower station should not be less than 16.7 m^3/s. Considering the future trend and safety margin, the minimum power generating flow of Pankou hydropower station is determined to be 20 m^3/s. The suggested peak shaving amplitudes is the allowance range of amplitudes that Pankou station satisfies all the requirements of water resources, as shown in Table 2.

Coordinated peak shaving results of cascade hydropower stations appears different as the daily average power flow of Pankou station Q changes. Firstly, if Q is more than 500 m^3/s, the discharge exceeds the regulation capacity of Xiaoxuan hydropower station, resulting in abandoned water on Xiaoxuan. In this case, Pankou hydropower station is suggested not taking part in the peak shaving operation. Secondly, if Q is between 300 and 500 m^3/s, the lord shaving amplitude should be within the range of suggested amplitudes. Otherwise, there may be abandoned water as the discharge of Pankou station exceeds. Furthermore, if Q is between 70 and 300m^3/s, Xiaoxuan hydropower station can totally anti-regulate Pankou hydropower station. In this case, Pankou hydropower station can take full part in the peak shaving operation and lord shaving amplitude can reach the maximum one. Finally, if Q is lower than 70 m^3/s, there may exist an unstable operation region for hydraulic generator units, which may probably result in the aggravation of unit vibration. In this case, Pankou hydropower station should not take part in peak shaving operation and it is important to go over the unstable region as quickly as possible to ensure the safe operation of units.

Table 2 Suggested peak shaving amplitude of Pankou hydropower station

Pankou reservoir water level (m)	Amplitude for different power generating flow rates (m^3/s) (ten MW)											
	Peak shaving model A						Peak shaving model B					
	100	200	300	400	500	600	100	200	300	400	500	600
330	7.60	22.80	36.00	35.85	0.00	0.00	7.60	22.80	36.00	35.85	0.00	0.00
335	8.60	24.60	39.42	39.34	0.00	0.00	8.60	24.60	39.42	39.34	0.00	0.00
340	9.60	26.60	42.80	32.20	0.00	0.00	9.60	26.60	42.80	32.20	0.00	0.00
345	10.40	28.60	45.80	34.20	0.00	0.00	10.40	28.60	45.80	34.00	0.00	0.00
350	11.40	30.20	48.60	36.80	0.00	0.00	11.40	30.20	48.60	36.60	0.00	0.00
355	12.20	32.00	50.91	37.77	0.00	0.00	12.20	32.00	50.91	37.77	0.00	0.00

4.3. Peak shaving operation of Xiaoxuan hydropower station
There are several choices for Xiaoxuan hydropower station when Pankou and Xiaoxuan cascade hydropower stations take part in the peak shaving operation, such as in synchronization with Pankou in peak shaving operation, no peak shaving operation and appropriate peak shaving operation are options.

Compared the advantage and disadvantage among three strategies above, Xiaoxuan hydropower station operates in synchronization with Pankou in short-term operation is preferred. This strategy is security and stable, which has been adopted by administration section in engineering application. So the power generating flow of Xiaoxuan hydropower station is preferably regulated in synchronization with Pankou hydropower station in this paper.

5. Conclusions
Short-term hydro generation scheduling is a good choice to carry out peak shaving in the power grid because of various outstanding properties. In order to deal with the SHGO problem, we developed a coordinated peak shaving operation method of cascade hydropower stations in this paper. This method is aim to maximize the amplitude of peak shaving while lord demand of power grid and water requirement of downstream are satisfied. The proposed method is applied to solve Pankou and Xiaoxuan cascade hydropower stations in Hanjiang River in China. Simulation results indicate that the proposed method can obtain suggested peak shaving amplitudes, which satisfies different operation demands of cascade hydropower stations in practical decision-making.

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