A Load-Based Method for Peak Operations of Cascaded Hydropower Stations

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Abstract. Short-term generation scheduling of cascade hydropower stations has always been one of the core tasks of power system operations. However, with the rapid increase of the number of power stations and the complexity of operation constraints, it is facing more and more challenges to quickly obtain practical day-ahead generation schedules. Based on the practical project of Hongshui River, a load-based method for peak operations of cascaded hydropower stations is proposed. The method takes the maximum effective generation production of cascaded hydropower stations as the objective, and introduces the generation weight coefficient by referring to load profile change. The purpose is to make the hydropower station generate power according to the priority of load peak, average and valley so that the generation schedules effectively meet the peak-shaving demand of the power grid. Moreover, a heuristic search procedure is developed to guide reasonable load distribution of hydropower stations. The method has been applied to a cascaded hydropower stations on the main stream of Hongshui River. The computational efficiency and rationality of the results have been verified in a case study, which shows that it is a feasible and practical method to solve the short-term operation problem of cascaded hydropower stations.

1. Introduction

Many giant cascaded hydropower stations have been exploited on large river basins, in Southwest China, such as Hongshui River, Lancang River, Wujiang River, etc [1-2]. These cascaded hydropower systems usually bear responsibility for important power generation operation tasks in power systems. Moreover, their operations are directly related to the security and economic benefits of power generation management apartments. It has always been an important work in the daily operation of power grids [3].

With the increasing demands of power grid for hydropower system, it is necessary not only to ensure the accuracy of power operation schemes, but also to meet the real-time performance of making generation schedules. From the view of the accuracy of power generation, in the short-term optimal operations of hydropower stations, it is necessary to meet the power system demands and operation constraints (such as peak-shaving, irregular restricted zones of huge units, etc.) [4-5]. From the view of the timeliness, it is required to reduce the optimization scale as far as possible and improve the efficiency of search and computation. These two issues may become more challenging for some large-scale cascaded hydropower systems which are composed of ten or even dozens of hydropower stations. In this case, the classical methods are usually difficult to efficiently deal with the problems of practical
projects [6]. Therefore, finding a fast, practical and convenient method of short-term generation scheduling for cascaded hydropower stations is crucial and necessary.

Based on the practical project of Hongshui River, a load-based method for peak operations of cascaded hydropower stations is proposed. The method takes the maximum effective generation production of cascaded hydropower stations as the objective, and introduces the generation weight coefficient by referring to load profile change. The purpose is to make the hydropower station generate power according to the priority of load peak, average and valley so that the generation schedules effectively meet the peak-shaving demand of the power grid. Moreover, a heuristic search procedure is developed to guide reasonable load distribution of hydropower stations. The method has been applied to a cascaded hydropower stations on the main stream of Hongshui River. The computational efficiency and rationality of the results have been verified in a case study, which shows that it is a feasible and practical method to solve the short-term operation problem of cascaded hydropower stations.

2. Mathematical Model

2.1. Nomenclature

t, T denote period index and its total number, respectively;
m, M denote station index and its total number, respectively;
Zm,t, Zm,t, Zm,t denote water level of reservoir m at the ending of period t, and its lower and upper limitations, respectively;
Vm,t is storage of reservoir m at the ending of period t;
Zd,m,t is tailrace water level of reservoir m at period t;
Hm,t is net water head of reservoir m at period t;
Qm,t is inflow of reservoir m at period t, Qm,t = Qn,m,t + \sum_{k=1}^{K_m} QT^k_{m,t};
K_m is total number of upstream power stations of the station m;
QT^k_{m,t} denotes the inflow of upstream station k into the reservoir m at period t;
Qn,m,t denotes local inflow of reservoir m at period t;
Ql,m,t denotes spillage discharge of reservoir m at period t;
p_m,t, p_m,t, p_m,t denote average generation of station m at period t, and its lower and upper limitations, respectively;
q_m,t, q_m,t, q_m,t denote power discharge of station m at period t, and its lower and upper limitations, respectively;
E_m, E_m' denote the calculated energy and specified target during time horizon, respectively.
Sm_t denotes total discharge of reservoir m at period t;
ps_{m,t,k}, ps_{m,t,k} denote maximum and minimum bounds of kth restricted zones of station m at period t;
\Delta_t is time duration at period t;
C_t is load demand at period t;
N_t, N_t, N_t denote total generation of hydropower system at period t, and its lower and upper bounds, respectively.
$pr_m$ is maximum climbing generation of station $m$;

$tc_m$, $tg_m$, $ts_m$ denote minimum time limitation for generation variation, start-up, and shut-down, respectively.

2.2. Objective
Considering all kinds of operation constraints and control requirements of hydropower station, and referring to the variation of power system load in one day, a specific load distribution rule is defined to guide the output distribution of hydropower station in different periods. The model introduces the power station output weight coefficient of each period, the goal is to achieve the maximum effective power output or generating capacity of all hydropower stations, so as to give full play to the ability of hydropower units to track load changes.

$$Max \ F = \sum_{t=1}^{T} \sum_{m=1}^{M} p_m \alpha(t, C_1, C_2, \cdots C_T, p_m, p_{m_1}, p_{m_2}, \cdots, p_{m_T})$$

where $\alpha(t, C_1, C_2, \cdots C_T, p_m, p_{m_1}, p_{m_2}, \cdots, p_{m_T})$ denotes weight coefficient of power station $m$ at period $t$, which depends on time period, load demand, generation profile, and load distribution rules.

2.3. Constraints
Water balance

$$V_{m,t+1} = V_{m,t} + 3600 \times (Q_m - q_m - Ql_m) \Delta t$$

Minimum and maximum hydropower generation

$$N_i \leq N_t \leq \bar{N}_t$$

Control target

$$E_m = E'_m$$

Minimum and maximum power discharge

$$q_{m_{\min}} \leq q_{m,t} \leq q_{m_{\max}}$$

Minimum and maximum reservoir discharge

$$S_{m_{\min}} \leq S_{m,t} \leq S_{m_{\max}}$$

Minimum and maximum power generation for one station

$$p_{m_{\min}} \leq p_{m,t} \leq p_{m_{\max}}$$

Minimum and maximum reservoir level

$$Z_{m_{\min}} \leq Z_{m,t} \leq Z_{m_{\max}}$$

Climbing generation limitation

$$pr_m \mid p_{m,t} - p_{m,t-1} \mid \geq 0$$

Minimum start-up and shut-down periods
\[
\begin{align*}
  p_{m,t} &> 0 \text{ if } p_{m,t-\tau_m} = 0 \text{ and } p_{m,t-1} > 0 \\
p_{m,t} &= 0 \text{ if } p_{m,t-\tau_m} > 0 \text{ and } p_{m,t-1} = 0 \\
p_{m,t} &\geq 0 \text{ otherwise}
\end{align*}
\]  

(10)

Restricted zones

\[
(p_{m,t} - \overline{ps}_{m,t,k})(p_{m,t} - \overline{ps}_{m,t,k}) > 0
\]  

(11)

Minimum working generation

\[
(p_{m,t} - p_{\min_m})p_{m,t} \geq 0
\]  

(12)

3. Solution Method

According to the above mathematical model, a specific load distribution method is designed to respond to the peak-shaving demands. The method can be described as: the order of increasing generation is peak, shoulder and low valley periods, and the order of reducing generation is opposite. When there are multiple peak periods, two peak shaving modes are provided, uniform peak-shaving and peak load ratio regulation. The former requires that the generation of a power station is basically equal in each peak period. In the latter way, the generation of each peak period is required to be in positive proportion to the peak load of the power grid. The order of increasing or decreasing output in each period varies with the process of power station output and system load.

\[
\alpha(t, C_1, C_2, \cdots, C_T, p_{m,1}, p_{m,2}, \cdots, p_{m,T}) = \alpha_1(t) + \alpha_2(t, C_1, C_2, \cdots, C_T, p_{m,1}, p_{m,2}, \cdots, p_{m,T})
\]  

(13)

where \(\alpha_1(t)\) represents the priority of peak, average and valley time, and is calculated according to the following formula

\[
\alpha_1(t) = \begin{cases} 
  b_1 & \text{t is peak periods} \\
  b_2 & \text{Other periods} \\
  b_3 & \text{t is off - peak period}
\end{cases} \quad b_1 > b_2 > b_3
\]  

(14)

where \(\alpha_2(t, C_1, C_2, \cdots, C_T, p_{m,1}, p_{m,2}, \cdots, p_{m,T})\) represents the priority of output distribution among multiple peak periods. This parameter is obtained by two steps. The first step is to determine the initial value by judging the position of \(t\), with the following formula

\[
\alpha_2 = \begin{cases} 
  \alpha'_2 & \text{t belongs to peak periods} \\
  0 & \text{Not}
\end{cases}
\]  

(15)

When the uniform peak-shaving way is used, the generation value \(p_{m,t}\) of the power station in each peak period is sorted in the ascend order, and the position of time periods after the sequence is denoted as \(o_t\).

\[
\alpha'_2 = c \times \frac{o_t}{Num_{peak} + 1}
\]  

(16)

where \(Num_{peak}\) is total number of peak periods; \(c\) is a conversion coefficient, which depends on \(b_1, b_2, b_3\), and \(c < b_1\).
When the peak load ratio regulation way is used, the minimum load period is firstly determined and denoted as $t'_1$; The ratio between the peak load value and the minimum peak load is calculated and denoted as $R_1(t)$; The ratio of output value of each power station in peak periods to minimum peak period is calculated and denoted as $R_2(t)$; The difference of proportion coefficient of each peak period is calculated using $R(t) = R_2(t) - R_1(t)$. The differences are ordered in a ascend order, meaning that the smaller the value of $R(t)$, the larger the period coefficient.

$$R_1(t) = \frac{C_i}{C_i}$$  \hspace{1cm} (17)

$$R_2(t) = \frac{P_{m,t}}{P_{m,i}}$$  \hspace{1cm} (18)

Thus, it can be seen that the output distribution order of the power station in peak, normal and valley periods is determined by $\alpha_1(t)$, while the output distribution sequence between all peak periods is determined by $\alpha_2$.

Coupled with the above well-designed load distribution rules and heuristic search method, the following procedure for short-term generation scheduling of hydropower stations is proposed. The procedure uses specific load distribution rules to conduct heuristic search to determine the 96-point operation schedules of hydropower stations. In order to meet the demand of heuristic search, a reverse search mode is introduced, that is, the downstream station affects the upstream station. For adjusting the operation state of the downstream power station, the generation, water level or outflow of the downstream power station are changed and fixed in part of the time, and the change of the downstream power station is feasible through the adjustment of the generation of each upstream power station. The detailed procedure is as follows.

**Step 1**: Data preparation, including operation parameters and curves.

**Step 2**: All power stations are ranked according to the hydraulic connection from upstream to downstream.

**Step 3**: In order to meet the given control demand of each station, the hydraulic connection between cascaded power stations is cut off, and the generation is distributed one by one according to the load distribution rules.

**Step 4**: Restore the hydraulic connection between cascaded hydropower stations, and calculate the regulation of each power station according to the method with fixed generation.

**Step 5**: The number of the adjusting station is $m$.

**Step 6**: Let $m = 1$.

**Step 7**: Determine whether there is spillage for the power station $m$. if so, calculate the weight coefficient of each period according to the load distribution rules, and increase the generation of the power station to eliminate the spillage. If it is still unable to meet the requirements, the upstream hydropower station will be affected to adjust the generation distribution between the periods. The hydropower station with better regulating performance will be given priority to adjust. The reverse search mode is adopted, that is, the inflow of the power station $m$ at some periods is reduced and fixed On the premise that the control conditions of the upstream power station are not damaged, the feasibility of adjusting its generation to make the inflow process of power station $m$ feasible; otherwise, the next step is taken.

**Step 8**: Compare the calculation results of power station $m$ with the given control target requirements. If the accuracy requirements are met, go to **Step 9**; otherwise, go to **Step 10**.
Step 9: The power station $m$ is adjusted by two directions, that is, the period with the minimum weight coefficient and the period with the largest weight coefficient are found, and the associated adjustment period is searched in their respective adjacent time intervals. Assuming that the minimum period of weight coefficient is $t_1$, the correlation search range is the area shown in $Z_1$; if the maximum time period of weight coefficient is $t_2$, the correlation search range is $Z_2$, and the generation are reduced and increased respectively according to a certain step size. If an improved operation scheme of the power station is obtained, go to Step 12; otherwise, go to the next step.

Step 10: The power station $m$ is adjusted in one direction, that is, the calculation target value is compared with the given target demand, and the direction of generation increase and decrease is determined. If the calculated final water level is less than the specified target, the generation needs to be reduced, and the relevant periods with the minimum weight coefficient are preferentially reduced; if the calculated final water level is greater than the specified target, the generation should be increased, and the period with the largest weight coefficient should be increased first.

Step 11: Repeat Step 10 until the calculated target value meets the given control demand. If it cannot be met, the reverse search mode is adopted, that is, modify the inflow of the power station $m$ in part periods and fix it, and adjust the generation of the upstream power station to ensure the feasibility of the storage profile of the power station $m$. The method of time interval selection is modified as follows: when it is necessary to reduce the inflow, the time lag between the two stations is subtracted according to the period when the weight coefficient of the upstream power station is small; when the time interval between the two stations is needed to be increased, the time lag between the two stations is subtracted according to the period when the weight coefficient of the upstream power station is larger.

Step 12: Coordinate the calculations. The downstream power station of the power station $m$ is calculated by the method with the fixed generation, to ensure that the generation at each period is as constant as possible, and the corresponding turbine discharge and final reservoir level are determined.

Step 13: Let $m = m + 1$, if $M < m$, return back to Step 7; otherwise, go to the next step.

Step 14: Judge whether the difference value of the objective function after two adjustments is within the accuracy range. If so, the calculation is finished; otherwise, return to Step 6.

4. Case Study

Taking the cascaded hydropower system in Hongshui River as an example, the daily operation scheme of 13 hydropower stations is made. The Hongshui River crosses Yunnan, Guizhou and Guangxi provinces, including Tianshengqiao I and Longtan hydropower stations with good regulating performance, seasonal regulation power stations such as Lubuge and Yunpeng, and some daily regulating power stations.

Figure 1 shows the variation process of load coefficient based on the load demand of China Southern Grid, which is mainly used to indicate the peak, average and valley periods of power system and load change trend. Since several peaks are close to each other, this case deals with the load distribution sequence between peak periods according to the uniform peak-shaving way in the conceptual peak regulation rules, and uses the above load distribution procedure to generate the 96-point operation schedules of cascaded hydropower stations. According to the load curve, three peak periods are defined as morning peak from 8:30 to 11:30, noon peak from 14:00 to 16:30, and late peak from 18:30 to 21:30. The shoulder load is from 7:00 to the beginning of early peak, from the end of late peak to 23:00, between morning and afternoon peak, and between noon and evening peak. The rest periods are load off-peak time.
Figure 1. The profile of load coefficient.

Figure 2 shows the total generation profile of 13 hydropower stations. It can be seen that the generation schedule is basically completed according to the distribution rules of peak, shoulder and off-peak. The day-ahead power generation of the power station is mainly concentrated in three peak periods. Since the load distribution sequence between peak periods is determined by the uniform peak-shaving method, the differences of generation values between morning, noon and evening peaks are small. Due to the limitation of climbing generation capacity between periods, a small amount of electricity is distributed in the shoulder load periods associated with peak hours, which is reasonable.

Figure 2. Power generation for the hydropower stations.

Figures 3 and 4 show the generation profiles of Tianshengqiao first reservoir and second station, respectively. Table 1 lists the optimization results of the two hydropower stations. It can be seen that the calculation results of each hydropower station avoids the restricted operation zones of generating units and meet the constraints of climbing generation limitations. Moreover, the generation of some hydropower stations is equal to or close to the given high-efficiency operation output value. Therefore, the calculation result is more reasonable.
Figure 3. Daily schedules for First reservoir of Tianshengqiao.

Figure 4. Daily schedules for Second Station of Tianshengqiao.

Table 1. Generation schedules for Tianshengqiao cascaded hydropower stations.

| Time   | Generation/MW | Time   | Generation/MW | Time   | Generation/MW | Time   | Generation/MW |
|--------|---------------|--------|---------------|--------|---------------|--------|---------------|
|        | I  | II  | I  | II | I  | II | I  | II | I  | II |
| 00:00  | 0  | 0   | 0  | 0  | 12:00 | 45  | 660  | 18:00 | 45  | 70  |
| 00:15  | 0  | 0   | 0  | 0  | 12:15 | 45  | 440  | 18:15 | 45  | 220 |
| 00:30  | 0  | 0   | 0  | 0  | 12:30 | 45  | 220  | 18:30 | 280 | 440 |
| 00:45  | 0  | 0   | 0  | 0  | 12:45 | 45  | 220  | 18:45 | 320 | 660 |
| 01:00  | 0  | 0   | 0  | 0  | 13:00 | 45  | 70   | 19:00 | 340 | 660 |
| 01:15  | 0  | 0   | 0  | 0  | 13:15 | 45  | 70   | 19:15 | 340 | 660 |
| 01:30  | 0  | 0   | 0  | 0  | 13:30 | 45  | 70   | 19:30 | 340 | 660 |
| 01:45  | 0  | 0   | 0  | 0  | 13:45 | 280 | 220  | 19:45 | 340 | 660 |
| 02:00  | 0  | 0   | 0  | 0  | 14:00 | 280 | 440  | 20:00 | 340 | 660 |
| 02:15  | 0  | 0   | 0  | 0  | 14:15 | 300 | 660  | 20:15 | 340 | 660 |
| 02:30  | 0  | 0   | 45 | 220 | 14:30 | 340 | 660  | 20:30 | 340 | 660 |
| 02:45  | 0  | 0   | 280| 440| 14:45 | 340 | 660  | 20:45 | 340 | 660 |
03:00  0  0  09:00  340  660  15:00  340  660  21:00  340  660
03:15  0  0  09:15  340  660  15:15  340  660  21:15  340  660
03:30  0  0  09:30  340  660  15:30  340  660  21:30  340  660
03:45  0  0  09:45  340  660  15:45  340  660  21:45  300  440
04:00  0  0  10:00  340  660  16:00  340  660  22:00  240  220
04:15  0  0  10:15  340  660  16:15  340  660  22:15  240  0
04:30  0  0  10:30  340  660  16:30  340  660  22:30  240  0
04:45  0  0  10:45  340  660  16:45  280  440  22:45  0  0
05:00  0  0  11:00  340  660  17:00  45  220  23:00  0  0
05:15  0  0  11:15  320  660  17:15  45  70  23:15  0  0
05:30  0  0  11:30  280  660  17:30  45  70  23:30  0  0
05:45  0  0  11:45  240  660  17:45  45  70  23:45  0  0

5. Conclusion
In this study, a load-based method for short-term peak operations are proposed to solve the short-term operation problem of cascaded hydropower stations in large river basin. The method is applied to the generation scheduling of cascaded hydropower stations in the main stream of Hongshui River, in western China. Two beneficial conclusions are obtained. On one hand, the variation of system load in one day can be employed to determine the reasonable weight coefficients that measure the generation proportion of the power station in each period. In this way, taking the effective power output or maximum generation production of the hydropower station as the goal can greatly realize the peak-shaving roles of large hydropower stations. On the other hand, the heuristic search based on the well-designed load distribution rules is able to quickly determine the power generation profile of the hydropower station, which is usually practical. Therefore, the proposed method provides a new insight and implementation technology for short-term generation scheduling of cascaded hydropower stations in large-scale basins.

Acknowledgments
The authors acknowledge the Open Research Fund of the Key Laboratory of Dynamics and Associated Process Regulations of the Pearl River Estuary, Ministry of Water Resources, under Grant [2018]KJ09, the Fundamental Research Funds for the Central Universities (DUT19JC43), the National Key R&D Program of China (2017YFC0405900) and the Key R&D Program of Guangxi Zhuang Autonomous Region (902229136010).

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