Energies **2015**, *8*, 11295-11314; doi:10.3390/en81011295

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Peak Operation of Cascaded Hydropower Plants Serving Multiple Provinces

Jianjian Shen [1,*], Chuntian Cheng [1,*], Jun Zhang [2] and Jianyu Lu [3]

[1] Institute of Hydropower and Hydroinformatics, Dalian University of Technology, Dalian 116024, Liaoning, China

[2] State Grid Zhejiang Electric Power Company, Hangzhou 310000, Zhejiang, China; E-Mail: zhang-jun@zj.sgcc.com.cn

[3] East China Electric Power Control Center, Shanghai 200122, China; E-Mail: lu_jy@ec.sgcc.com.cn

* Authors to whom correspondence should be addressed; E-Mails: shenjj@dlut.edu.cn (J.S.); ctcheng@dlut.edu.cn (C.C.); Tel.: +86-411-8470-8468 (J.S. & C.C.).

Academic Editor: Juan Pérez-Díaz

Received: 18 May 2015 / Accepted: 8 October 2015 / Published: 13 October 2015

Abstract: The bulk hydropower transmission via trans-provincial and trans-regional power networks in China provides great operational flexibility to dispatch power resources between multiple power grids. This is very beneficial to alleviate the tremendous peak load pressure of most provincial power grids. This study places the focus on peak operations of cascaded hydropower plants serving multiple provinces under a regional connected AC/DC network. The objective is to respond to peak loads of multiple provincial power grids simultaneously. A two-stage search method is developed for this problem. In the first stage, a load reconstruction strategy is proposed to combine multiple load curves of power grids into a total load curve. The purpose is to deal with different load features in load magnitudes, peaks and valleys. A mutative-scale optimization method is then used to determine the generation schedules of hydropower plants. In the second stage, an exterior point search method is established to allocate the generation among multiple receiving power grids. This method produces an initial solution using the load shedding algorithm, and further improves it by iteratively coordinating the generation among different power grids. The proposed method was implemented to the operations of cascaded hydropower plants on Xin-Fu River and another on Hongshui River. The optimization results in two cases satisfied the peak demands of receiving provincial power grids. Moreover, the maximum load difference between peak and valley decreased 12.67% and 11.32% in Shanghai Power Grid (SHPG) and Zhejiang Power Grid (ZJPG), exceeding by 4.85% and 6.72% those of the current operational method, respectively. The advantage of the proposed method in alleviating peak-shaving pressure is demonstrated.

Keywords: cascaded hydropower plants; optimal operation; peak operation; two-stage search method; multiple provinces

---

1. Introduction

Hydropower is the largest renewable generation source in China, representing 22.3% of the total national capacity [1]. Hydropower systems take major responsibility for meeting fast growing power demands, especially peak load demands, in China's expanding electricity grid [2–4]. With the commissioned nationwide ultra-high voltage AC/DC network [5], many cascaded hydropower plants or large hydropower plants need to transmit power to several provincial or regional power grids at the same time. Moreover, there has been a substantial increase in the scale of power transmission with the fast growth of China's hydropower development. By the end of 2014, the maximum transmission capacity has reached 74 GW, representing one fourth of the total hydropower capacity in China. The bulk hydropower transmission via trans-provincial and trans-regional power networks provides great operational flexibility to dispatch power resources between interconnected multiple power grids. This is very beneficial to alleviate the tremendous peak load pressure on most power grids.

This study focuses on the peak operation of hydropower plants serving multiple provinces under a regional connected AC/DC network. These kinds of hydropower plants are usually operated by a central dispatching authority (CDA) of a regional power grid. The CDA is responsible for determining their operational schedules and allocating the power generation to multiple subordinate provincial power grids. The main objective is to respond simultaneously to the peak load demands of subordinate provincial power grids. As an example, the cascaded hydropower plants on the Hongshui River such as Tianshengqiao and Longtan, are directly operated by the China Southern Power Grid (Figure 1). They provide electricity for Guangdong and Guangxi provinces. Their operational objective is to shave peak loads for the two provincial power grids. In this problem, the major difficulty is the greatly different load demands among multiple provincial power grids with respect to magnitude, peak value and number, and the timing of peak and light loads. These differences make it very hard to determine the quarter-hourly generation schedule of hydropower plants. An additional difficulty is imposed by the complex electricity coupling between plants and power grids, as well as hydraulic relation and many plant operation constraints. Therefore, the main concern of this work is how to dispatch the hydropower sources serving multiple provinces while satisfying various operational conditions and constraints. The main goal is to find a feasible and practical solution for this problem to alleviate the increasing peak-shaving pressures of receiving power grids in eastern and coastal China.

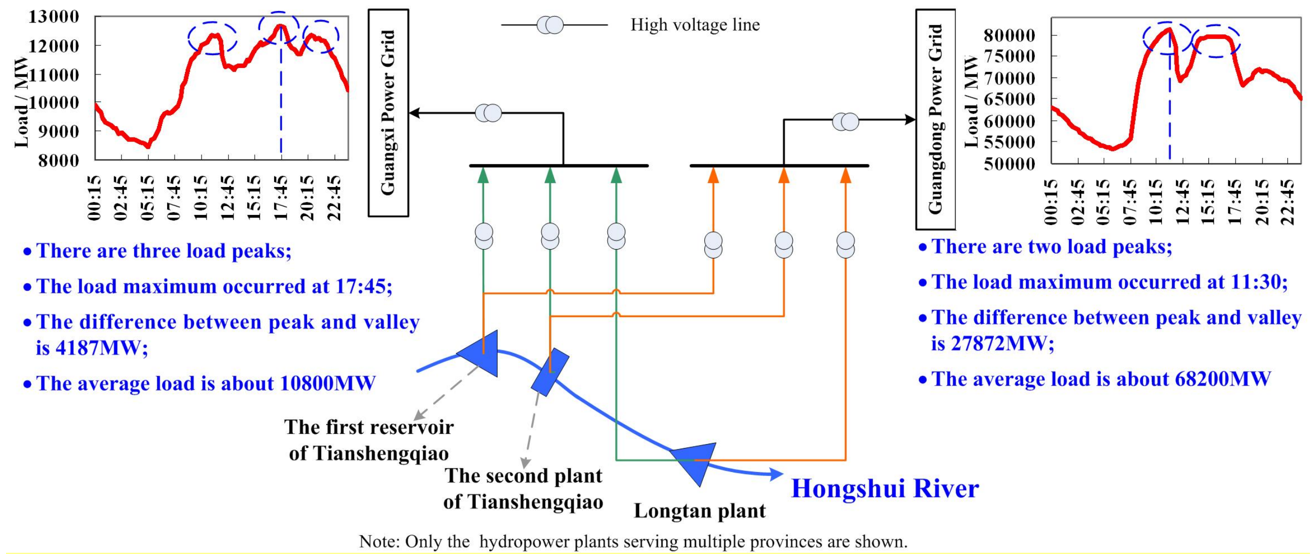


Figure 1. An example of cascaded hydropower plants serving multiple provinces.

Mathematically, the above problem is a highly nonlinear and nonconvex optimization problem with the nonlinear objective function of peak shaving and large amounts of spatial-temporal coupling system and plant operation constraints [6,7]. The simplification of such complex objective functions and constraints make it hard to obtain directly an analytic solution or a discrete optimum using linear programming [8,9], nonlinear programming [10–12], or dynamic programming [13–15]. Moreover, these analytic methods are closely dependent on the computable requirements of available commercial software. In practice, they often require considerable amounts of effort and time to reformulate the original problem while responding to frequent changes and requirements of plants and power grids. Thus, their applications to the current real-world problem are hindered. Besides, the artificial intelligence and population-based algorithms [16,17] are also not suitable for practical hydropower system operations because the optimal results are usually instable. This is unacceptable for system operators. For such a complicated optimization problem, a commonly used way is to decompose the original problem into several easily solved subproblems [18–21] according to the characteristics of the considered hydropower system. This method is also employed in the study.

In this paper, the cascaded hydropower plants on Xin-Fu River and another on Hongshui River are taken as the examples. The former is operated by the China Southern Power Grid covering Guangdong, Guangxi, Yunnan, Guizhou, and Hainan provinces. The second is controlled by the East China Grid covering Shanghai, Jiangsu, Zhejiang, Anhui, and Fujian provinces. The power transmission and operations of the two cascaded hydropower plants under the regional connected AC/DC networks is representative of the situation in China. Each large hydropower plant provides electricity for several provincial power grids with greatly different load demands, as shown in Figure 1. It is very different from the traditional operation problem for a single power grid. Hence, this study intends to develop a suitable method for the peak operations of this kind of cascaded hydropower plants. A two-stage search method is thus developed. In the first stage, a load reconstruction strategy is developed to combine multiple load curves of provincial power grids into a total load curve. The purpose is to deal with different load features in load magnitudes, peaks and valleys. A mutative-scale optimization method is then used to determine the generation schedules of cascaded hydropower plants. In the second stage, an exterior point search method is established to allocate the generation among multiple receiving power grids. The initial solution is produced using the load shedding algorithm. Afterwards, the solution is gradually improved by iteratively coordinating peak power among different power grids according to load changes during one day. The results from the two cases indicated that the proposed method met the different peak demands of multiple provincial power grids. Moreover, this method presented advantages over real operation. The maximum load difference between peak and valley decreased 12.67% and 11.32% in the Shanghai Power Grid (SHPG) and Zhejiang Power Grid (ZJPG), exceeding by 4.85% and 6.72% those of the current operational method, respectively. Hence, the method was practicable, and useful, to schedule hydropower plants serving multiple provinces.

2. Model Description

2.1. The Objective Function

The centralized dispatch method is currently adopted in China to optimize power operations [22,23]. In this mode, system security and supply-demand balance are the priorities. Among them, response to peak demands during high load hours is of vital importance. Usually, hydropower plants are first required to respond to peak loads because of the advantages of quick start and high climbing speed of hydro generating units. The remaining load, which is obtained by deducting hydropower generation from the original load, is further assigned to low regulating coal-fired plants and other plants. The reason is that the smoothed load curves can effectively reduce the start and stop times of coal-fired units and then save energy resources. Therefore, the main goal considered in this study is to shave peak loads and smooth remaining load for low regulating power plants. According to our previous work [22,23], minimizing the mean square deviation of the remaining load is suited as the optimization objective for the peak operation of cascaded hydropower plants:

$$\min F = \sum_{t=1}^{T}[(C_t - \sum_{m=1}^{M} p_{m,t}) - \sum_{i=1}^{T}(C_i - \sum_{m=1}^{M} p_{m,i})/T]^2 \tag{1}$$

When the cascaded hydropower plants serve multiple provinces, they need to satisfy peak load requirements of multiple provincial power grids at the same time. Obviously, this problem is a multi-objective optimization. It is needed to minimize the mean square deviation of the remaining load of all power grids being considered. Correspondingly, the optimization objective is formulated as:

$$\min F_g = \sum_{t=1}^{T}[(C_{g,t} - \sum_{m=1}^{M} p_{m,g,t}) - \sum_{i=1}^{T}(C_{g,i} - \sum_{m=1}^{M} p_{m,g,i})/T]^2 \tag{2}$$

This multi-objective optimization problem is transformed to a single objective problem by determining objective weights [24–26]. The objective function becomes:

$$\min F = \sum_{g=1}^{G} w_g \times \frac{F_g}{C_{g,\max}^2} \tag{3}$$

The weight coefficients have an important influence on the optimization. They are dependent on the requirements of shaving peak load for power grids. Generally, the power grid with strong peak-shaving needs should be given much consideration. It means the weight coefficient is bigger. In the real world, most of provincial power grids in China face big peak-shaving pressure during high load hours.

The power grids considered in later case studies are just so. It is equally important for these power grids to meet their peak demands. Therefore, all weight coefficients are set equal to $1/G$ in this study. Besides, there is usually big difference of load magnitudes among multiple provincial power grids, which may cause unreasonable optimization results. To avoid this, the load maximum of each power grid is introduced to normalize the remaining load in the objective function.

2.2. Constraint Conditions

The water balance is:

$$V_{m,t+1} = V_{m,t} + 3600 \times (Q_{m,t} - q_{m,t} - Qd_{m,t})\Delta_t \tag{4}$$

The control requirement for the daily energy production from plant m is:

$$E_m = E'_m \tag{5}$$

The transmitted energy from one plant to power grid g is established as follows:

$$\sum_{t=1}^{T} p_{m,g,t} \times \Delta_t = E_m \times R_{m,g} \tag{6}$$

The power balance in any a period is expressed as:

$$\sum_{g=1}^{G} p_{m,g,t} = p_{m,t} \tag{7}$$

The turbine discharge capacity for each plant is formulated as follows:

$$\underline{q}_{m,t} \le q_{m,t} \le \overline{q}_{m,t} \tag{8}$$

The total discharge bounds for each reservoir is:

$$\underline{S}_{m,t} \le S_{m,t} \le \overline{S}_{m,t} \tag{9}$$

The generation capacity of plant m is:

$$\underline{p}_{m,t} \le p_{m,t} \le \overline{p}_{m,t} \tag{10}$$

The minimum and maximum reservoir water level of plant m is:

$$\underline{Z}_{m,t} \le Z_{m,t} \le \overline{Z}_{m,t} \tag{11}$$

The maximum ramping capacity for power generation of plant m is expressed by:

$$\begin{cases} (1+\mu_m)\overline{p}_{m,t-1} - p_{m,t} \ge 0, & p_{m,t} > p_{m,t-1} \\ (1-\mu_m)\overline{p}_{m,t-1} - p_{m,t} \le 0, & p_{m,t} \le p_{m,t-1} \end{cases} \tag{12}$$

The minimum operation and shutdown time requirements for plant m:

When plant m is generating at period $t - t_{s,m}$:

$$\text{If } p_{m,t-1} = 0 \text{ then } p_{m,t} = 0 \tag{13}$$

When plant m is shut down at period $t - t_{g,m}$:

$$\text{If } p_{m,t-1} > 0 \text{ then } p_{m,t} > 0 \tag{14}$$

The above two constraints play an important role in avoiding frequent start-up and shut-down of the hydropower plant.

The forbidden zones of plant *m* are:

$$(p_{m,t} - \overline{ps}_{m,t,k})(p_{m,t} - \underline{ps}_{m,t,k}) > 0 \tag{15}$$

The minimum generation output of plant *m* is:

$$(p_{m,t} - p_{\min,m})p_{m,t} \geq 0 \tag{16}$$

3. The Two-Stage Search Method

3.1. Solution Framework

Generally, the choice of methods depends on the characteristics of the optimization problem. The peak operation of hydropower plants serving multiple provinces involves very complex objective function and spatial-temporal coupling constraints. It is hard to directly obtain analytic solutions or a discrete optimum using mathematical programming methods. A feasible way is decomposing the original problem into relatively simple subproblems according to the operation tasks. Hence, a two-stage search method is developed for the peak operation of cascaded hydropower plants serving multiple provinces. In this method, the original problem was divided into two subproblems: determining the optimal generation schedule of hydropower plants, and allocating the generation among receiving power grids. The first subproblem is addressed using a mutative-scale optimization method based on a load reconstruction strategy. With the known generation schedules of hydropower plants, the second subproblem is handled by an exterior point search method. A solution framework is established in the second stage to iteratively improve the generation schedule and its allocation among multiple power grids, shown in Figure 2. In the iterative procedure, the mutative-scale optimization method and exterior point search method are repeatedly employed. They will be discussed in the following two subsections, respectively. In the last subsection, a total solution procedure is given.

3.2. The Mutative-Scale Optimization Method Based on Load Reconstruction Strategy

The mutative-scale optimization method based on load reconstruction strategy is proposed to determine the generation of each hydropower plant. Two steps are needed in the solution process of this method. The first step is reconstructing a total load curve using the load reconstruction strategy. Based on the obtained total load curve, the mutative-scale optimization method is used to optimize the generation schedules of hydropower plants.

3.2.1. Step 1: Reconstructing a Total Load Curve

Generally, the daily load curves of multiple provincial power grids are not synchronous in magnitude and the timing of peak and off-peak loads. These factors add great difficulty on scheduling hydropower plants. Therefore, this paper attempts to combine all load curves into a total one. The goal is to determine the generation of hydropower plants according to the total load curve. However, the cumulative curve is dependent on the power grid with the biggest load value, not reflecting the characteristics of peak and off-peak load of other power grids. Therefore, the allocation proportion of the generated energy among power grids is introduced to reconstruct a total load curve from multiple load curves. The formulation is expressed as:

$$C_t = \sum_{g=1}^{G} R_{m,g} \times C_{g,t} \times \frac{C_{g,t} - C_{g,\min}}{C_{g,\max} - C_{g,\min}}, \quad 1 \le t \le T \tag{17}$$

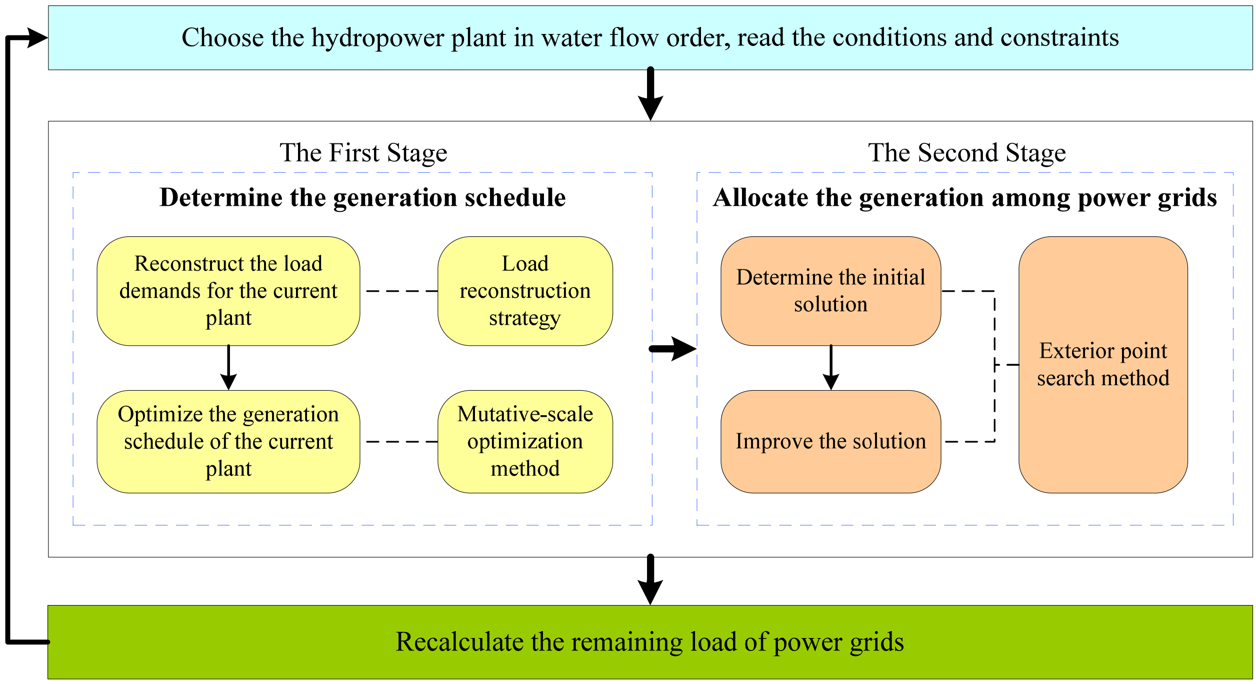


Figure 2. Solution framework.

3.2.2. Step 2: Determining the Generation Schedule of Hydropower Plants

With the combined load curve in the above step, the first subproblem is transformed into a readily solved one. The solution methods for such a problem have been extensively reported in the literature [27]. Here the mutative-scale optimization method is adopted to solve the problem. In this method, the original problem is decomposed into a set of subproblems with larger time intervals, where the feasible range of decision variables is greatly increased by weakening or even eliminating coupling constraints such as Equations (12)–(14). Moreover, the number of computational stages is also reduced. Taking the hydro scheduling problem with 15 min interval for example, the procedure of this method is given as follows:

(a) Change the original problem into four kinds of subproblems with time intervals of 6 h, 3 h, 1.5 h and 15 min respectively, as shown in Figure 3.

(b) Start to optimize these subproblems successively from the largest time interval of 6 h using the progressive optimality algorithm (POA). The detail about POA and its solution procedure for the hydropower operations can refer to the literature [22].

For one subproblem, the power generation at period t is initialized equal to the generation value at period t' in the previous larger-step problem, where $t' = t/\alpha$; α is a multiple made by dividing the previous time step by the current one; $1 \leq t \leq T$. Correspondingly, the required discharge for fixed generation $p_{m,t}$ ($1 \leq t \leq T$) is computed by use of the relationship among power generation, discharge and head. On the other hand, the constraints in Equations (12)–(14) need to be redefined with the required time step. The constraint in Equation (12) is rewritten by the following formulation:

$$\begin{cases} (1+\beta\times\mu_m/2)\overline{p}_{m,t-1}-p_{m,t}\geq 0 & \text{if } p_{m,t}>p_{m,t-1} \\ (1-\beta\times\mu_m/2)\overline{p}_{m,t-1}-p_{m,t}\leq 0 & \text{otherwise} \end{cases} \tag{18}$$

The constraints in Equations (13) and (14) are changed into:

When plant m is generating at period $t - t_{s,m}/\beta$:

$$\text{If } p_{m,t-1} = 0 \text{ then } p_{m,t} = 0 \tag{19}$$

When plant m is shut down at period $t - t_{g,m}/\beta$:

$$\text{If } p_{m,t-1} > 0 \text{ then } p_{m,t} > 0 \tag{20}$$

(c) Generate an initial solution for the subproblem with time interval of 3 h according to the optimal solution from the current time step (such as 6 h).

(d) Update the current subproblem with next time interval and solve it.

(e) Repeat the above process until the time interval is equal to 15 min.

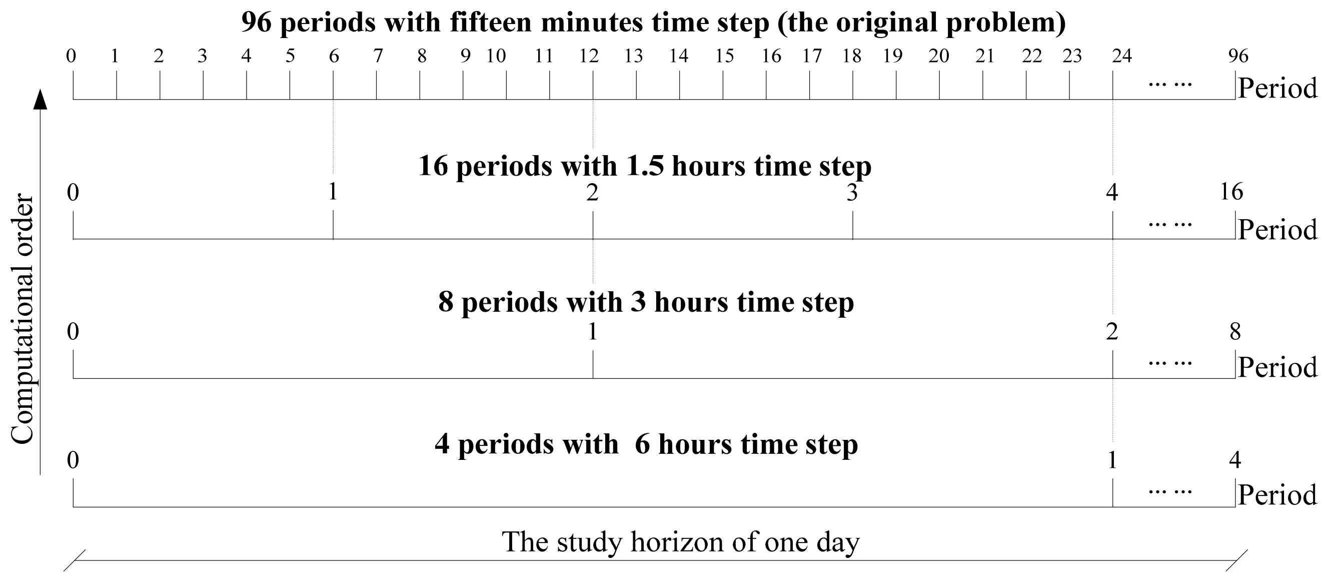


Figure 3. Different time scales for a set of short-term hydro scheduling problems.

3.3. The Exterior Point Search Method for Allocating Generation among Power Grids

The second subproblem focuses on allocating generation among provincial power grids after the day-ahead quarter-hourly generations from hydropower plants are obtained. The basic idea is to coordinate the generation among multiple power grids using their load differences, particularly those occurring during the time of peak loads. Related research has rarely been reported. Therefore, this study proposed an exterior point search method to solve the problem. The method consists of two key parts: generate an initial solution and coordinate the generation among power grids:

3.3.1. Generate an Initial Solution by the Load Shedding Algorithm

The load shedding algorithm is a commonly used way in China. It is applied to determine the generation schedule of one plant while the total energy demand and load curve over the entire time horizon are given [28]. Here, the total energy transmitted to each power grid can be easily calculated with Equation (21):

$$E_{m,g} = E_m \times R_{m,g} \tag{21}$$

To generate the initial solution, the procedure of load shedding algorithm is outlined:

Calculate $C_{g,max} - P_{m,max}$, and then determine the initial shedding position on the load curve shown in Figure 4; where $C_{g,max}$ = $\max\left\{C_{g,1}, C_{g,2}, \cdots, C_{g,T}\right\}$ and $P_{m,max}$ = available generation capacity of plant m; After determining the shedding position, calculate the total energy $E'_{m,g}$ (the grey area in Figure 4), and compare it with the specified $E_{m,g}$; If $E'_{m,g} > E_{m,g}$, move up the shedding position; else if $E'_{m,g} < E_{m,g}$, move down the shedding position. In the moving process, if $P_{m,t} > P_{m,max}$, then set $P_{m,t} = P_{m,max}$; Repeat the above process until $E'_{m,g} = E_{m,g}$.

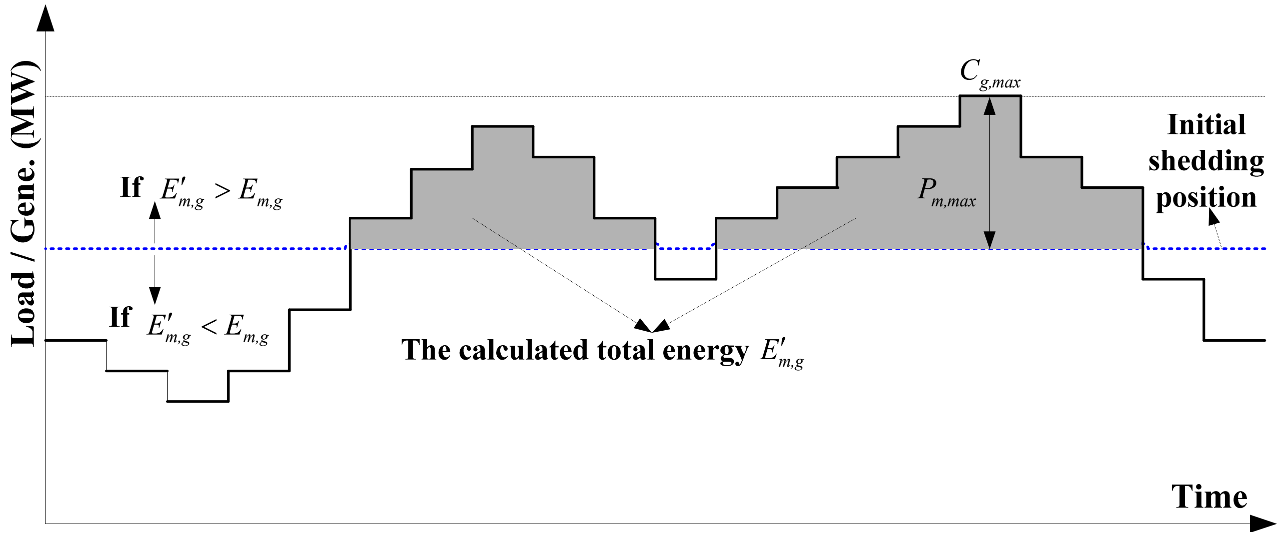
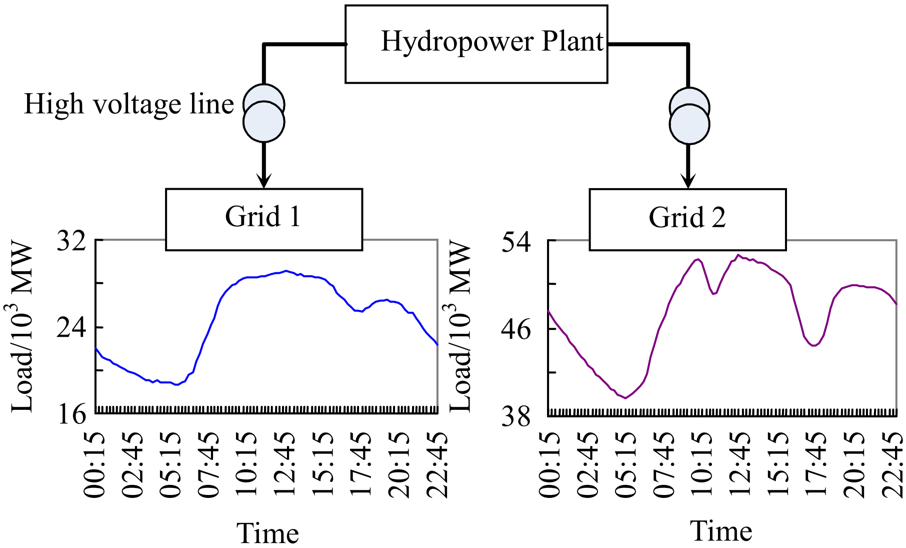
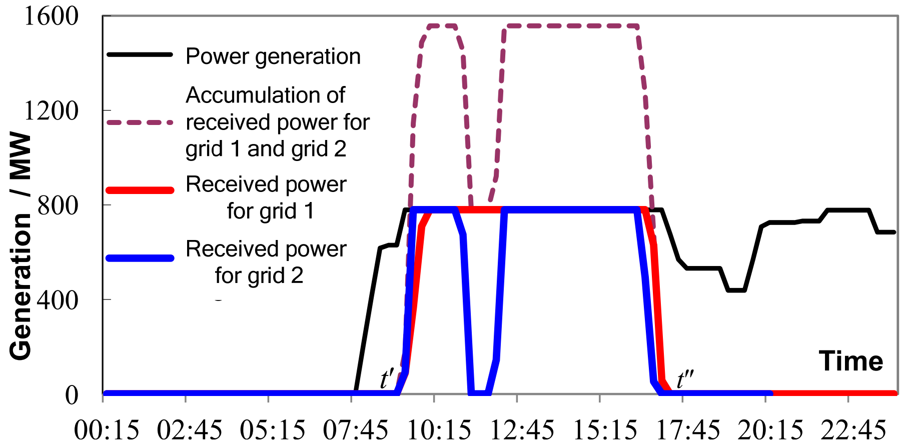


Figure 4. The principle of load shedding algorithm.

Figure 5a gives a general example, where a single hydropower plant provides electricity for two provincial power grids. As mentioned above, this kind of plant is usually operated by the dispatching authority of a regional power grid and connected to the subordinate provincial power grids via high voltage lines. It provides the generated energy for each provincial grid with the specified ratio in the electricity contract. Thus, the above load shedding algorithm can easily produce an initial transmission schedule shown in Figure 5b. However, this solution violated the power balance constraint in Equation (7). Therefore, the second part will improve this solution.



(a)



(b)

Figure 5. (**a**) A general example about power transmission via trans-provincial power network; and (**b**) initial solution for the exterior point search method.

3.3.2. Mainly Improving the Initial Solution Obtained Above

A heuristic strategy, which decreases the generation output during lowest load hours and increases the generation output during highest load hours, is adopted. As an example presented in Figure 5, this strategy will guide the transfer of the power generation from the period interval [t', t''] to other periods till the power balance is attained at each period. The detailed procedure is illustrated below.

Step 1: Find Period t_1 to Reduce Generation

Calculate the generation positive deviation vector $D_t = \{D_1, D_2, \ldots, D_T\}$ using Equation (22), and then find the maximum of elements $\max|D_t|$. The corresponding period is denoted as t_1:

$$D_t = \begin{cases} \sum_{g=1}^{G} p_{m,g,t} - p_{m,t}, & \sum_{g=1}^{G} p_{m,g,t} > p_{m,t} \\ 0, & \text{else} \end{cases} \tag{22}$$

Step 2: Find Power Grid g' to Adjust the Received Generation

Calculate the order number O_{g,t_1} of the remaining load C'_{g,t_1} in descending order, $1 \le g \le G$; and then find $\max\left\{O_{1,t_1}, O_{2,t_1}, \cdots, O_{G,t_1}\right\}$. The corresponding power grid number is denoted as g'.

Step 3: Find Period t_2 to Increase Generation

Calculate the generation minus deviation vector $D'_t = \{D'_1, D'_2, \ldots, D'_T\}$ using Equation (23). Similarly, the corresponding period of the maximum element $\max|D'_t|$ is denoted as t_2:

$$D_t = \begin{cases} 0, & \sum_{g=1}^{G} p_{m,g,t} \ge p_{m,t} \\ \sum_{g=1}^{G} p_{m,g,t} - p_{m,t}, & \text{else} \end{cases} \tag{23}$$

Step 4: Adjust the Generation Transmitted to Power Grid g'

Determine the step size p_d with Equation (24), and respectively decrease and increase the received generations of power grid g' at period t_1 and t_2, with Equations (25) and (26). Recalculate the remaining load of power grid g'. Afterwards, the process returns to Step 2:

$$p_d = \min\{\max D_t, \max\left|D'_t\right|, p_D\} \tag{24}$$

$$P_{m,g',t1} = P_{m,g',t1} - p_d \tag{25}$$

$$P_{m,g',t2} = P_{m,g',t2} + p_d \tag{26}$$

3.4. The Solution Procedure of the Two-Stage Method

The whole procedure of the two-stage search method is summarized as follows:

Step 1: Read the initial conditions, including operation constraints for hydropower plants, the load demand curve of each power grid, and the specified proportion of energy transmitted to each power grid;

Step 2: Number the hydropower plant as m;

Step 3: Determine the load demands $\{C_1, C_2, \ldots, C_T\}$ for plant m using Equation (17);

Step 4: With the objective function in Equation (1), and constraints in Equations (4), (5) and (9)–(16), optimize the generation output of plant m using mutative-scale optimization method presented in the Section 3.2.

Step 5: With the equality constraints in Equations (6) and (7), allocate the generation from plant m among G power grids through exterior point search method. The result is denoted as $\{p_{m,1,1}, p_{m,1,2}, \ldots, p_{m,1,T}\}$, $\{p_{m,2,1}, p_{m,2,2}, \ldots, p_{m,2,T}\}$, …, $\{p_{m,G,1}, p_{m,G,2}, \ldots, p_{m,G,T}\}$;

Step 6: Recalculate the remaining loads of each power grid using Equation (27):

$$C'_{g,t} = C_{g,t} - \sum_{m=1}^{M} p_{m,g,t} \tag{27}$$

where $C'_{g,t}$ (MW) is the remaining load of power grid g in period t.

Step 7: Set $m = m + 1$. If $m \leq M$, go back to Step 3. Otherwise, go to Step 8.

Step 8: Calculate the objective value of the current solution using Equation (3) and compare with the last objective value. If the solution is improved, take the current solution as the initial solution for the next iteration, and go back to Step 2. Otherwise, go to Step 9.

Step 9: If the current iteration reaches the specified maximum, obtain the optimization results and then stop; otherwise, go back to Step 2.

4. Case Studies

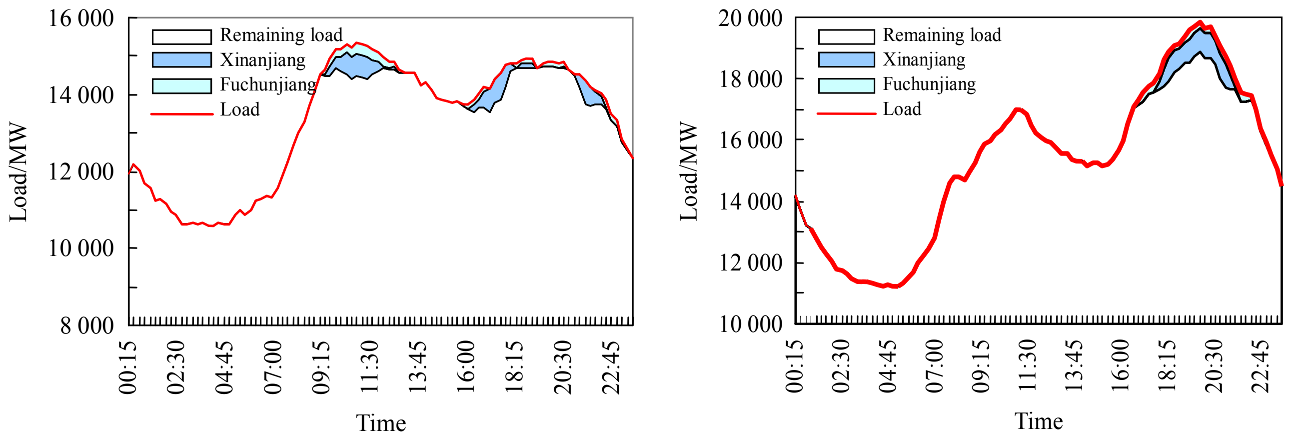
4.1. Cascaded Hydropower Plants on the Xin-Fu River

Two hydropower plants are built on the Xin-Fu River, Xinanjiang upstream and Fuchunjiang downstream. They are operated by the East China Grid (the largest regional power grid in China). Their responsibility is to provide power especially peak power for two subordinate provincial power grids, Shanghai and Zhejiang. Table 1 shows the details of two hydropower plants. To test the proposed method, two typical daily load curves of SHPG and ZJPG in February and August 2013, was chosen and denoted by Scheme 1 or 2, respectively. Moreover, the optimization results were compared with actual generation records to further validate the efficiency of this method.

Table 1. Characteristics of cascaded hydropower plants built on the Xin-Fu River.

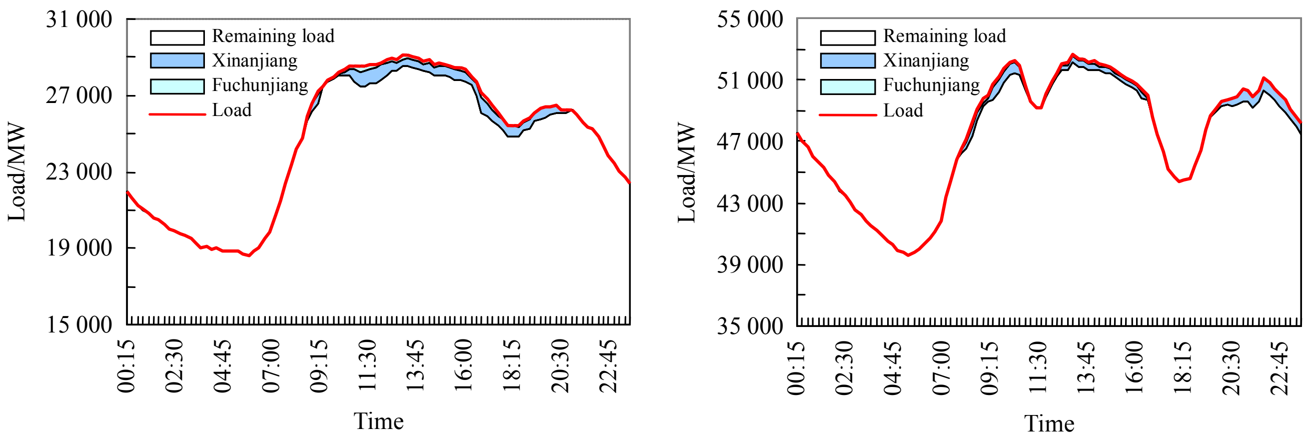
Hydropower plant	Installation capacity/MW	Regulating ability	Transmission proportion/%		Energy demand/MWh	
			Shanghai	Zhejiang	Scheme 1	Scheme 2
Xinanjiang	850	Yearly	50	50	5200	11,400
Fuchunjiang	354	Daily	50	50	2900	2900

Figures 6 and 7 present the load balance results in Schemes 1 and 2, respectively. Figure 8 shows the generation profiles of hydropower plants in Scheme 2. Table 2 illustrates the indices for peak operation in Scheme 2. Figure 6 indicates that there were significant differences in peak load and peak time between SHPG and ZJPG in Scheme 1. SHPG showed morning and evening load peaks and the former is bigger than the latter. However, ZJPG mainly has an evening load peak, significantly higher than the load in any other period. Therefore, it is reasonable that ZJPG received a lot of power during the evening peak hours while SHPG did so during the morning and evening peak hours. This implied the proposed method took full advantage of the load differences between the two power grids. Table 2 shows that in Scheme 1, the load differences between peak and valley of SHPG and ZJPG decreased 12.67% and 11.32%, respectively. Correspondingly, the mean square deviation of the remaining load decreased by 8.17% and 8.81%, respectively. It indicates that the peak load pressure of power grids was effectively alleviated. The smoothed remaining load would be advantageous to the operation of low regulating coal-fired units.



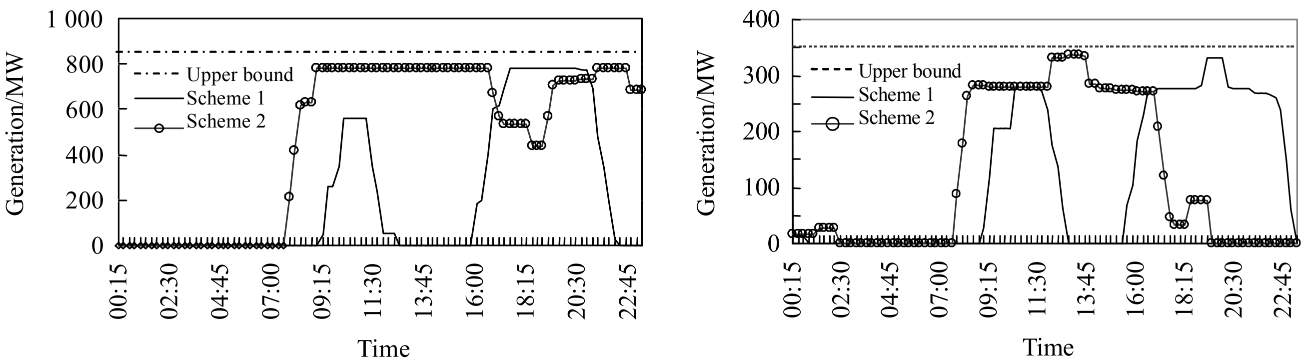
(**a**) (**b**)

Figure 6. Load balance profiles in Scheme 1: (**a**) Shanghai Power Grid (SHPG); and (**b**) Zhejiang Power Grid (ZJPG).



(**a**) (**b**)

Figure 7. Load balance profiles in Scheme 2: (**a**) SHPG; and (**b**) ZJPG.



(**a**) (**b**)

Figure 8. Generation output of plants in certain periods: (**a**) Xinanjiang Plant; and (**b**) Fuchunjiang Plant.

Table 2. Comparison of the optimal results from two methods.

Scheme	Power grids	Maximum difference of original load/MW	Our method		Real operation	
			Maximum difference of remaining load/MW	Reduction/%	Maximum difference of remaining load/MW	Reduction/%
1	SHPG	469	4165	12.67	4396	7.82
	ZJPG	8645	7666	11.32	8247.5	4.60
2	SHPG	10,491	9918	5.46	9948	5.18
	ZJPG	13.062	12,480	4.46	12,520	4.15
Scheme	**Power grids**	**Mean square deviation of original load/MW**	**Our method**		**Real operation**	
			Mean square deviation of remaining load/MW	**Reduction/%**	**Mean square deviation of remaining load/MW**	**Reduction/%**
1	SHPG	1624	1491	8.17	1487	8.40
	ZJPG	2557	2332	8.81	2427	5.06
2	SHPG	3632	3382	6.88	3426	5.65
	ZJPG	3958	3731	5.74	3761	4.99

In Scheme 2, there exists a great difference in load demands between the SHPG and ZJPG. In particular, the magnitude of load in ZJPG was far bigger than that in SHPG. As seen from Figure 7 and Table 2, rational generation schedules were provided by the proposed method. The ZJPG mainly received electricity in the morning, noon, and evening peak hours. The maximum load difference between peak and valley in a day was reduced by 582 MW, about 4.46%. SHPG received abundant electricity in the daytime peak periods, which was also consistent with its load curve. There exists large decrease of 573 MW in the maximum load difference between peak and valley. This proved that the optimized results effectively respond to the peak demands of both power grids.

As can be shown in Figure 8, Xinanjiang and Fuchunjiang hydropower plants worked with the nearly maximum generation capacity during peak hours 10:00–16:30. A minority of the energy production is generated during other high load periods to satisfy continuous generation output requirements such as generation climbing constraint and the minimum continuous startup and stop times. Consequently, the generation schedules of two hydropower plants were rational and feasible.

Moreover, the optimized results of Scheme 1 were compared with actual operational records, as shown in Figure 9 and Table 2. Our method produces smaller load difference between peak and valley for each provincial power grid than the real operation. The variations reached 4.85% and 6.72% in SHPG and ZJPG, respectively. Similarly, the square deviation value of the remaining loads was also reduced. This implies the real-world operation which allocated the power generation of each period among provincial power grids with the fixed proportions in the contracts is not efficient. Therefore, the load differences between provincial power grids should be fully employed to efficiently schedule the hydropower plants.

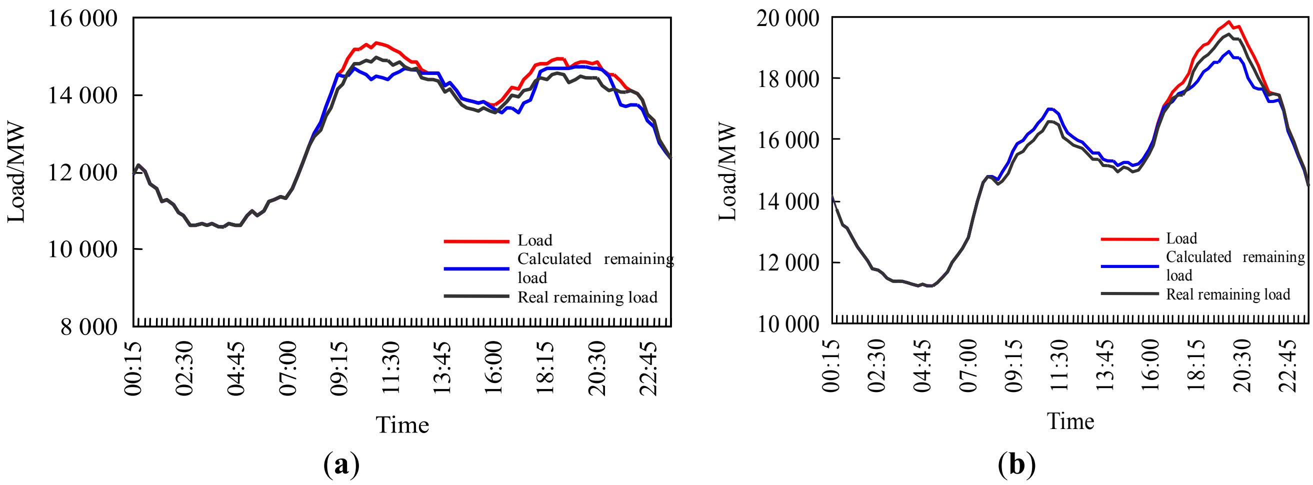


Figure 9. Comparison between the optimal results of Scheme 1 and real values; (**a**) SHPG; and (**b**) ZJPG.

4.2. Cascaded Hydropower Plants on Hongshui River

In Case 2, the proposed method is implemented to the operation of cascaded hydropower plant on Hongshui River. Hongshui River is one of the 13 largest hydropower bases in China (named as Nanpanjiang–Hongshui River Hydropower Base). This river is one of the earliest exploited hydropower bases in China. Ten hydropower plants have been planned in its main stream, nine of which have been put into operation from upstream Tianshengqiao to downstream Qiaogong plant, with an installed capacity of 10,739 MW (shown in Table 3). Among them, Tianshengqiao-1, Tianshengqiao-2, and Longtan operated by SCPG, are responsible to provide power for Guangdong Power Grid (GDPG) and Guangxi Power Grid (GXPG). The three hydropower plants have the major responsibility for shaving peak loads of power grids by using their regulating capability and large installed capacity (about 69% of total capacity). Due to hydraulic connection, four cascaded hydropower plants, *i.e.*, Tianshengqiao-1, Tianshengqiao-2, Pingban, and Longtan, are chosen in this case. The generation schedules and its allocation among two grids were made by the proposed method. Figure 10 shows the overall optimal results. Figure 11 gives the generation profiles of the four plants, respectively.

Table 3. Detailed characteristics for cascaded hydropower plants on Hongshui River.

Hydropower plant	Installation capacity/MW	Regulating ability	Transmission proportion/%		Energy demand/MWh
			Guangxi	Guangdong	
Tianshengqiao-1	1200	Yearly	50	50	11,700
Tianshengqiao-2	1320	Daily	50	50	17,500
Pingban	405	Daily	100	-	3,400
Longtan	4900	Yearly	50	50	20,700

The optimization results showed that hydropower plants mainly generated during high load hours. The load peaks of GDPG and GXPG were effectively shaved. The corresponding remaining load curves were smoother than those in real-world operation. This demonstrated that our method produced rational and efficient results. Compared with Scheme 1 in Case 1, the load magnitude difference between GDPG and GXPG was apparently bigger. The mean load value in the former was approximately 6.3 times that in the latter. Therefore, the variation range of peak loads in GDPG was much smaller than that in GXPG, although the two power grids received same power energy from hydropower plants. The maximum load difference between peak and valley decreased by 6% in the GDPG whilst 44% in the GXPG. Figure 10 also shows the result clearly. This situation implies that the load demands had a significant impact on optimizing the generation schedules of hydropower plants among power grids.

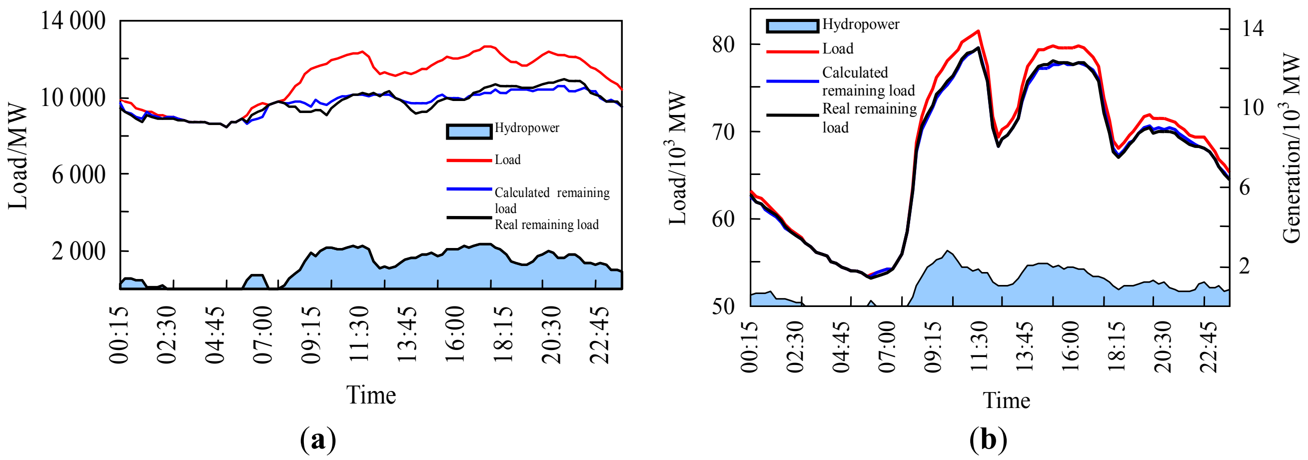


Figure 10. Optimal results for cascaded hydropower plants on Hongshui River: (**a**) Guangxi Power Grid (GXPG); and (**b**) Guangdong Power Grid (GDPG).

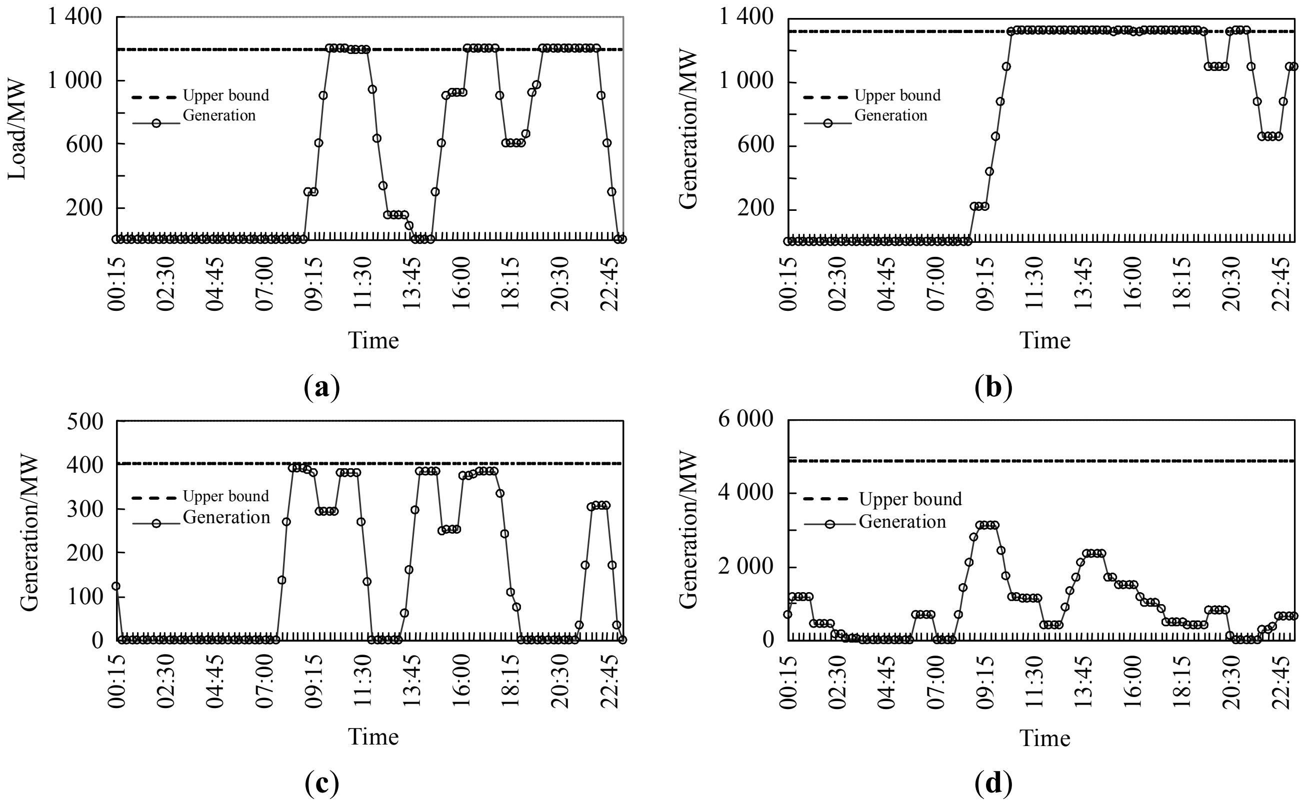


Figure 11. Generation profiles of each hydropower plant: (**a**) Tianshengqiao-1 Plant; (**b**) Tianshengqiao-2 Plant; (**c**) Pingban Plant; and (**d**) Longtan Plant.

In summary, the above two cases indicate that the proposed two-stage search method presents excellent adaptability to schedule the hydropower plants and coordinate their generation among power grids. It is valid and efficient way to respond to the peak load demands of different provincial power grids. Moreover, this method is capable of producing better results than the conventional method used in real-world engineering.

5. Conclusions

In the near future, the operation and optimization of China's hydropower system will become more complex with the explosive growth of the scale of trans-provincial and trans-regional hydropower transmission. Hydropower operations involve more complex requirements of the receiving power grids, especially peak load demands. The peak operation of hydropower plants will be a useful and effective tool to alleviate the tremendous peak pressure on most power grids in China. This study presents a two-stage search method for this kind of problems, taking the cascaded hydropower systems on Xin-Fu River and Hongshui River as examples. The method can effectively coordinate and allocate the power generation of hydropower plants among provincial power grids through utilizing differences on load characteristics. Furthermore, there were bigger decreases in the load differences between peak and valley, and the mean square deviation of the remaining load, than the real operation. This indicates that the proposed method is capable of producing rational and efficient generation operational schedules. A sensitivity analysis indicates our method is robust in handling greatly different load demand conditions.

It should be mentioned that the proposed method has been successfully used to provide decision support to the system operators of the East China Grid and China Southern Power Grid to make the day-ahead quarter-hourly generation schedules. This method plays a significant role in alleviating the increasing peak-shaving pressure of these power grids. Besides, power losses are an important factor during the long-distance power transmission. This was not included in the current method as this study mainly emphasizes the peak operation of hydropower plants. Our future works will study and discuss the impact of the power losses on the generation dispatch and load distribution.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Nos. 51209031, 51579029, and 51025934), Chinese Postdoctoral Science Special Foundation (No. 2013T60284), and the Fundamental Research Funds for the Central Universities (No. DUT14RC(3)089). The writers are very grateful to the anonymous reviewers and editors for their constructive comments.

Author Contributions

Jianjian Shen and Chuntian Cheng are the primary authors of this manuscript; the other authors participated in the discussion, and provided the support for engineering data and testing the method.

Conflicts of Interest

The authors declare no conflict of interest.

Acronyms

SHPG	Shanghai Power Grid
ZJPG	Zhejiang Power Grid
GDPG	Guangdong Power Grid
GXPG	Guangxi Power Grid

Variables

$P_{m,t}$	Power generation of plant *m* at period *t*, in MW;
C_t	Remaining power load of the power grid at period *t*; $1 \leq m \leq M$, in MW;
M	Total number of plants;
T	Total number of time periods during the operational horizon;
t	Time period index;
$P_{m,g,t}$	Generation output transmitted to power grid *g* by plant *m* in period *t*, in MW;
G	Total number of power grids;
g	Power grid index;
w_g	Objective weight of power grid *g*;
$C_{g,\max}$, $C_{g,\min}$	Maximum and minimum load of power grid *g*, in MW;
$V_{m,t}$	Storage capacity of plant *m* in period *t,* in m^3/s;
$Q_{m,t}$	Reservoir inflow of plant *m* in period *t* and $Q_{m,t} = Qn_{m,t} + \sum_{k=1}^{K} QT_{m,t}^{k}$, in m^3/s;
K	Total number of upstream plants of plant *m*;
$QT_{m,t}^{k}$	Discharge of upstream plant *k* into plant *m* in period *t* by considering the time delay, in m^3/s;
$Qn_{m,t}$	Local inflow of plant *m* in period *t*, in m^3/s;
$Qd_{m,t}$	Spill water of the reservoir *m* in period *t*, in m^3/s;
E_m, E'_m	Calculated energy production from plant *m* during the operational horizon and the specified value, in MWh;
$R_{m,g}$	Proportion of the power transmitted to power grid *g* by plant *m*, and $\sum_{g=1}^{G} R_{m,g} = 1$;
$q_{m,t}$, $\overline{q}_{m,t}$, $\underline{q}_{m,t}$	Turbine discharge of plant *m* in period *t*, the upper bound, and lower bound, in m^3/s;
$S_{m,t}$, $\overline{S}_{m,t}$, $\underline{S}_{m,t}$	Total discharge(turbine discharge plus spill) of reservoir *m* in period *t*, the upper bound, and lower bound, in m^3/s;
$\overline{p}_{m,t}$, $\underline{p}_{m,t}$	Maximum and minimum generation output of plant *m* in period *t*, in MW;
$Z_{m,t}$, $\overline{Z}_{m,t}$, $\underline{Z}_{m,t}$	Reservoir level of plant *m* in period *t*, and its maximum and minimum water levels, in m;
μ_m	Ramping rate for generation output of plant *m*;
$t_{g,m}$	Minimum duration of operation periods for hydropower plant *m*;
$t_{s,m}$	Minimum duration of shutdown periods for hydropower plant *m*;
$\overline{ps}_{m,t,k}$, $\underline{ps}_{m,t,k}$	Maximum and minimum of the *k*th forbidden zone of plant *m* in period *t*, in MW;

$p_{\min,m}$	Minimum generation of plant *m* when in operation, in MW;
β	A multiple made by dividing the current time step by 15 min;
$E_{m,g}$	Total energy from plant *m* transmitted to power grid *g*, in MWh;
p_D	Maximum generation amplitude in the iterative correction process, in MW.

References

1. Cheng, C.T.; Shen, J.J.; Wu, X.Y.; Chau, K.W. Operation challenges for fast-growing China's hydropower systems and respondence to energy saving and emission reduction. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2386–2393.
2. Cheng, C.T.; Wang, S.; Chau, K.W.; Wu, X.Y. Parallel discrete differential dynamic programming for multireservoir operation. *Environ. Model. Softw.* **2014**, *57*, 152–164.
3. Guo, S.L.; Chen, J.H.; Li, Y.; Liu, P.; Li, T.Y. Joint operation of the multi-reservoir system of the Three Gorges and the Qingjiang cascade reservoirs. *Energies* **2011**, *4*, 1036–1050.
4. Zhang, R.; Zhou, J.Z.; Zhang, H.F. Optimal Operation of Large-Scale Cascaded Hydropower Systems in the Upper Reaches of the Yangtze River, China. *J. Water Resour. Plan. Manag.* **2014**, *140*, 480–495.
5. Huang, D.C.; Shu, Y.B.; Ruan, J.J.; Hu, Y. Ultra High Voltage Transmission in China: Developments, Current Status, and Future Prospects. *Proc. IEEE* **2009**, *97*, 555–583.
6. Xu, B.; Zhong, P.A.; Wan, X.Y.; Zhang, W.G.; Chen, X. Dynamic Feasible Region Genetic Algorithm for Optimal Operation of a Multi-Reservoir System. *Energies* **2012**, *5*, 2894–2910.
7. Kuo, M.T.; Lu, S.D. Experimental Research and Control Strategy of Pumped Storage Units Dispatching in the Taiwan Power System Considering Transmission Line Limits. *Energies* **2013**, *6*, 3224–3244.
8. Shawwash, Z.K.; Siu, T.K.; Denis Russell, S.O. The BC hydro short term hydro scheduling optimization model. *IEEE Trans. Power Syst.* **2000**, *15*, 1125–1131.
9. Momoh, J.A.; El-Hawary, M.E.; Adapa, R. A review of selected optimal power flow literature to 1993, Part II: Newton, linear programming and interior point methods. *IEEE Trans. Power Syst.* **1999**, *14*, 105–111.
10. Sivasubramani, S.; Swarup, K.S. Hybrid DE-SQP algorithm for non-convex short term hydrothermal scheduling problem. *Energy Convers. Manag.* **2011**, *52*, 757–766.
11. Finardi, E.C.; Silva, E.L. Solving the hydro unit commitment problem via dual decomposition and sequential quadratic programming. *IEEE Trans. Power Syst.* **2006**, *24*, 835–843.
12. Finardi, E.; Da Silva, E.; Sagastizabal, C. Solving the unit commitment problem of hydropower plants via Lagrangian relaxation and sequential quadratic programming. *Comput. Appl. Math.* **2005**, *24*, 317–341.
13. Zhao, T.T.G.; Zhao, J.S.; Yang, D.W. Improved Dynamic Programming for Hydropower Reservoir Operation. *J. Water Resour. Plan. Manag.* **2014**, *140*, 365–374.
14. Park, H.G.; Lyu, J.K.; Kang, Y.; Park, J.K. Unit Commitment Considering Interruptible Load for Power System Operation with Wind Power. *Energies* **2014**, *7*, 4281–4299.
15. Yi, J.; Labadie, J.W.; Stitt, S. Dynamic optimal unit commitment and loading in hydropower systems. *J. Water Resour. Plan. Manag.* **2003**, *129*, 388–398.

16. Zhang, H.F.; Zhou, J.Z.; Zhang, Y.C.; Lu, Y.L.; Wang, Y.Q. Culture belief based multi-objective hybrid differential evolutionary algorithm in short term hydrothermal scheduling. *Energy Convers. Manag.* **2013**, *65*, 173–184.
17. Moeini, R.; Afshar, M.H. Extension of the constrained ant colony optimization algorithms for the optimal operation of multi-reservoir systems. *J. Hydroinf.* **2013**, *15*, 155–173.
18. Takigawa, F.Y.K.; da Silva, E.L.; Finardi, E.C.; Rodrigues, R.N. Solving the hydrothermal scheduling problem considering network constraints. *Electr. Power Syst. Res.* **2012**, *88*, 89–97.
19. Petcharaks, N.; Ongsakul, W. Hybrid enhanced Lagrangian relaxation and quadratic programming for hydrothermal scheduling. *Electr. Power Compon. Syst.* **2007**, *35*, 19–42.
20. Dieu, V.N.; Ongsakul, W. Improved merit order and augmented Lagrange Hopfield network for short term hydrothermal scheduling. *Energy Convers. Manag.* **2009**, *50*, 3015–3023.
21. Al-Agtash, S. Hydrothermal scheduling by augmented Lagrangian: Consideration of transmission constraints and pumped-storage units. *IEEE Trans. Power Syst.* **2011**, *16*, 750–756.
22. Cheng, C.T.; Shen, J.J.; Wu, X.Y. Short-Term Scheduling for Large-Scale Cascaded Hydropower System with Multi-Vibration Zones of High Head. *J. Water Resour. Plan. Manag.* **2012**, *138*, 257–267.
23. Cheng, C.T.; Shen, J.J.; Wu, X.Y. Short-term hydro scheduling with discrepant objectives using multi-steps of progressive optimality algorithm. *J. Am. Water Res. Assoc.* **2012**, *48*, 464–479.
24. Selvakumar, A.I. Civilized swarm optimization for multiobjective short-term hydrothermal scheduling. *Int. J. Electr. Power Energy Syst.* **2013**, *51*, 178–189.
25. Jubril, A.M.; Komolafe, O.A.; Alawode, K.O. Solving Multi-objective economic dispatch problem via semidefinite programming. *IEEE Trans. Power Syst.* **2013**, *28*, 2056–2064.
26. Chiang, C.L. Optimal economic emission dispatch of hydrothermal power systems. *Int. J. Electr. Power Energy Syst.* **2011**, *33*, 647–656.
27. Labadie, J.W. Optimal Operation of Multireservoir Systems: State-of-the-Art Review. *J. Water Resour. Plan. Manag.* **2004**, *130*, 93–111.
28. Wang, J.Y.; Shen, J.J.; Cheng, C.T. A load shedding method for thermal power plants with peak regulation based on load reconstruction strategy. *Proc. CSEE* **2014**, *34*, 2684–2692. (In Chinese)