Short-Term Scheduling of Expected Output-Sensitive Cascaded Hydro Systems Considering the Provision of Reserve Services

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Abstract: The integration of large-scale wind and solar power into the power grid brings new challenges to the security and stability of power systems because of the uncertainty and intermittence of wind and solar power. This sensitive expected output has real implications for short-term hydro scheduling (STHS), which provides reserve services to alleviate electrical perturbations from wind and solar power. This paper places an emphasis on the sensitive expected output characteristics of hydro plants and their effect on reserve services. The multi-step progressive optimality algorithm (MSPOA) is used for the STHS problem. An iterative approximation method is proposed to determine the forebay level and output under the condition of the sensitive expected output. Cascaded hydro plants in the Wujiang River are selected as an example. The results illustrate that the method can achieve good performance for peak shaving and reserve services. The proposed approach is both accurate and computationally acceptable so that the obtained hydropower schedules are in accordance with practical circumstances and the reserve can cope with renewable power fluctuations effectively.

Keywords: short-term hydro scheduling; peak shaving; multi-step progressive optimality algorithm; sensitive expected output; reserve services

1. Introduction

By the end of 2018, the total installed hydropower capacity in China was 352 GW, and the annual hydropower generation was 1.2 trillion kWh, both of which continue to rank first in the world [1]. There are bulk hydropower plants with a large installed capacity and high head in Southwest China. These plants not only have great environmental benefits with regard to the reduction of coal consumption and carbon emissions but also play an important role in a national project named Electricity Transmission from West to East.

The coal-fired power plant is a reliable energy source because it does not depend on the existing climatic conditions. However, coal-fired power costs more than hydropower in peak shaving because coal-fired power plants cannot start up and shut down flexibly. Large-sized hydro plants perform the important task of peak regulation and reserve services in Southwest China. As a result, the head may change greatly, which is very different from other hydro plants, whose head variation is negligible [2]. Figure 1a shows the tail water level-water discharge curve of the GPT reservoir in Southwest China. The tail water level can vary by 6.7 m with the discharge variation within a day. The head loss is usually a quadratic function of the turbine flow [3], which aggravates the variation of the net head.
Furthermore, these plants’ expected outputs are often sensitive to the net head, and their expected output is the maximum output under a certain head. The GPT reservoir’s net head–expected output curve is shown in Figure 1b. The expected output can vary by as much as 385 MW, with the net head varying 8.9 m within a day. The sensitive expected output has real implications for short-term hydro scheduling, and the implications are more noticeable when providing reserve services.

It is worth mentioning that the performance of a hydro unit depends on the turbine flow and on the net head [4]. The maximum output of a unit for a specific value of the head can be obtained from the unit performance curves. However, the relationship between the maximum output and the net head becomes ambiguous when the unit performance curves are converted into the performance of a hydro plant. Therefore, the net head–expected output curve of a hydro plant is introduced to characterize the relationship between the maximum output and the net head.

Related studies that take head-sensitive cascaded hydro plants into account achieve good results [5,6]. Reference [5] considers the head-dependent water-power conversion and adds another dimension of difficulty, since the outputs of the hydro plants are no longer stage-wise additive with respect to water discharge. However, the influence of the head on the expected output is neglected, which needs to be considered in this study. Hydro plants in [7] provide reserve services, but the expected output equals the capacity of the hydro plant and this simplification is not feasible in this study, especially in the dry season. Expected output is considered to be a function of the head in [8], but there is no further analysis of the impact on reserve services in the case of large-scale grid integration of wind and solar power into the power grid.

By the end of 2019, the wind and solar power capacities in China were 210.05 GW and 204.30 GW, respectively. Table 1 illustrates the wind and solar power capacities in China from 2005 to 2019. The integration of large-scale wind and solar power into the power grid brings new challenges to the security and stability of the power systems because of the uncertainty and intermittence of wind and solar power [9].

| Energy Resource | 2005 | 2010 | 2015 | 2019 |
|-----------------|------|------|------|------|
| Wind            | 1.26 | 30   | 131  | 210.05 |
| Solar           | 0.07 | 0.3  | 42   | 204.30 |

The data was obtained from the official website of the China National Energy Administration.

Much of the research performed in the past two decades has been devoted to coping with this challenge. Many results suggest that the coordinated operation of a hydro–wind–solar system shows good compensation benefits [10]. Abundant reserves provided by hydro plants are needed to alleviate...
electrical perturbations from wind and solar power [9]. The sensitive expected output characteristic makes the reserve supplied by hydro plants volatile. It is certainly possible that hydro plants can supply the required reserve at the current period but cannot satisfy the reserve demands during subsequent periods because the expected output decreases with the reduction of the net head.

This paper places an emphasis on the sensitive expected output characteristic of hydro plants and its effect to the reserve services. The solution techniques proposed in the past few decades include linear programming (LP) [11], the nonlinear approach [8], mixed integer programming (MIP) [12,13], dynamic programming (DP) [14,15], Lagrangian relaxation (LR) [16,17] and the Benders decomposition approach [18,19]. In addition to the abovementioned mathematical approaches, heuristic methods include the genetic algorithm (GA) [20], particle swarm optimization (PSO) [21], the artificial neural network (ANN) [22], simulated annealing (SA) [23], ant colony optimization (ACO) [24] and the harmony search algorithm (HSA) [25]. More techniques are described in [26,27].

It is still very challenging to model nonlinear characteristics through MILP techniques due to the accumulated linearization error [26]. The variable solution has limited the applications of heuristic methods because of the unavoidable stochastic search mechanism [28]. The STHS problem is nonlinear and nonconvex with interconnected hydraulic and electrical linking [3]. These complex links can be solved effectively by the progressive optimality algorithm (POA). However, the POA easily falls into the local optimum and is also sensitive to its initial solution. To overcome this limitation, the MSPOA is used to improve the quality of the optimal solutions and enhance the convergence speed [29]. An iterative approximation method is introduced under the solution framework of the MSPOA to determine the forebay level and output in the case of the sensitive expected output.

This paper is organized as follows. The STHS problem is formulated in Section 2. Section 3 presents the whole solution framework. Section 4 provides a case study based on cascaded hydro plants in the Wujiang River, one of the thirteen hydropower bases in China. Section 5 concludes the paper.

2. Problem Formulation

In a liberalized electricity market, a goal of maximizing profits is usually used [8,30]. Peak shaving is often chosen as the objective in a monopolistic power system, and the power grid ensures the power balance during every period in the whole system [3,31]. The Chinese power system is a typical example [9]. Furthermore, wind and solar power curtailments are usually not allowed except during congestion in the transmission network.

The frequency distribution of the errors between planned and actual schedules can be obtained from historical wind and solar power data. The error boundary values are determined by statistical analysis based on confidence interval estimation theory. In this way, the uncertainty and intermittence of wind and solar power can be compensated by reserve services that are supplied by cascaded hydro plants. Then, the coordinated operation of a hydro-wind-solar system is simplified into an STHS problem under reserve constraints [9].

In general, the reserve includes the spinning reserve and non-spinning reserve. For a large-sized hydro plant, there is a period of a few minutes from no power generation to full power generation. In addition, the start-up cost of the hydro unit is relatively small [32]. As a result, the spinning reserve and non-spinning reserve are not strictly distinguished in this study, and both are regarded as the reserve, including the up reserve and down reserve.

Due to the influence of the flow lag time of upstream and downstream hydro plants, a time horizon of 7 days is considered and divided into hourly intervals.
2.1. Objective Function

In China, a major goal of power system operations is to alleviate the load differences between the peaks and the off-peaks for many low-efficiency coal-fired units [33]. To achieve this goal, the objective function is to minimize the standard deviation of the residual load and is expressed as

$$\min F = \sqrt{\frac{1}{T} \sum_{t=1}^{T} (D'_t - \bar{D}')^2}$$

(1)

where

$$D'_t = D_t - \sum_{r=1}^{R} p_{r,t}$$

(2)

where $R$ and $r$ are the set and index of reservoirs, respectively; $T$ and $t$ are the set and index of hours in the time horizon, respectively; $D_t$ is the power load at period $t$; $D'_t$ is the residual load at period $t$; $\bar{D}'$ is the average value of $D'_t$; and $p_{r,t}$ is the output of plant $r$ at period $t$. Subscripts $r$ and $t$ are the indexes of reservoirs and periods, respectively, in the following sections.

2.2. Constraints

(1) Initial and terminal forebay levels: The terminal forebay level is obtained from the long-term hydro scheduling:

$$z_{r,0}^{up} = z_{r,0}^{beg}, \quad z_{r,T}^{up} = z_{r,end}$$

(3)

where $z_r^{beg}$ and $z_r^{end}$ are the initial and terminal forebay levels, respectively, and $z_r^{up}$ is the forebay level.

(2) Continuity equation:

$$v_{r,t+1} = v_{r,t} + \left( d_{r,t} + \sum_{k=1}^{NU} u_{k,t-T_{k,r}} - u_{r,t} \right) \times \Delta t$$

(4)

where $v_{r,t}$ is the water storage; $d_{r,t}$ is the local inflow; $NU$ is the number of upstream plants directly above the $r$th hydro plant; $u_{r,t}$ is the water discharge; and $u_{k,t-T_{k,r}}$ is the water discharge of the $k$th hydro plant at period $(t - \Gamma_{k,r})$. $\Gamma_{k,r}$ is the water time delay between hydro plants $k$ and $r$.

(3) Water discharge equation:

$$u_{r,t} = q_{r,t} + s_{r,t}$$

(5)

where $q_{r,t}$ and $s_{r,t}$ are the turbine flow and water spillage, respectively.

(4) Net head equation:

$$h_{r,t} = z_{r,t}^{up} - z_{r,t}^{down} - \Delta h_{r,t}$$

$$z_{r,t}^{up} = f_{r}^{co}(v_{r,t})$$

$$z_{r,t}^{down} = f_{r}^{co}(u_{r,t})$$

$$\Delta h_{r,t} = \alpha_r q_{r,t}^2 + h_{r}^{loss}$$

(6)

where $h_{r,t}$ and $\Delta h_{r,t}$ are the net head and head loss, respectively; $z_{r,t}^{down}$ is the tail water level; $\alpha_r$ and $h_{r}^{loss}$ are the head loss coefficient and the head loss constant, respectively; $f_{r}^{co}(v_{r,t})$ is the forebay level-storage curve; and $f_{r}^{co}(u_{r,t})$ is the tail water level-water discharge curve.

(5) Power ramping constraint:

$$|p_{r,t+1} - p_{r,t}| \leq \Delta p_r$$

(7)

where $\Delta p_r$ is the maximum power ramp.
(6) Hydroelectric power generation characteristics function:
\[ p_{r,t} = f_r^e(h_{r,t})q_{r,t} \]  
where \( f_r^e(h_{r,t}) \) is the producibility coefficient of a plant.

(7) Expected output function:
\[ \overline{p}_{r,t} = f_{r,\text{E}}^o(h_{r,t}) \]
where \( \overline{p}_{r,t} \) is the expected output and \( f_{r,\text{E}}^o(h_{r,t}) \) is the expected output function.

(8) Up reserve constraints:
\[ \sum_{r=1}^{R} (\overline{p}_{r,t} - p_{r,t}) \geq UR_t \]  
where \( UR_t \) is the up reserve limit.

(9) Down reserve constraints:
\[ \sum_{r=1}^{R} (p_{r,t} - \overline{p}_{r,t}) \geq DR_t \]  
where \( DR_t \) is the down reserve limit and \( \overline{p}_{r,t} \) is the minimum output limit.

(10) Forebay level, output, turbine flow and water discharge limits:
\[ Z_{r,t}^{\text{up}} \leq z_{r,t} \leq Z_{r,t}^{\text{up}} \]
\[ p_{r,t} \leq p_{r,t} \leq \overline{p}_{r,t} \]
\[ Q_{r,t} \leq q_{r,t} \leq Q_{r,t} \]
\[ U_{r,t} \leq u_{r,t} \leq U_{r,t} \]

where \( Z_{r,t}^{\text{up}} \) and \( Z_{r,t}^{\text{up}} \) are the lower and upper forebay level limits, respectively; \( Q_{r,t} \) and \( Q_{r,t} \) are the minimum and maximum turbine flow limits, respectively; and \( U_{r,t} \) and \( U_{r,t} \) are the minimum and maximum water discharge limits, respectively.

3. Model Solution

3.1. Determination of the Required Up Reserve

As mentioned previously, the uncertainty and intermittence of wind and solar power are transformed into reserve constraints for an STHS problem. The up reserve and down reserve can be determined by statistical analysis of historical wind and solar power data. More details can be found in [9]. It should be noted that due to the sensitivity of the expected output, when the up reserve is used at this period, the reserve constraints may not be met at the next several periods for the decrease of the net head. This risk actually occurs in China. To avoid this situation, a safety factor is introduced and expressed as
\[ UR^{*}_t = UR_t \times \delta \]
where \( UR^{*}_t \) is the required up reserve and \( \delta \) is the safety factor, which is greater than 1.

\( \delta \) is related to the duration of the schedule errors, the sensitivity of the expected output and the regulating ability of hydro plants. These factors cause difficulty in determining \( \delta \) and the determination has been simplified by artificial experience in this study.
3.2. Overview of the MSPOA

The POA decomposes a multi-stage decision problem into a series of two-stage subproblems, which can effectively alleviate the curse of dimensionality [34,35]. When solving the current subproblem, the current state variable will be dispersed into a series of values, and the other state variables remain unchanged. Once an improved trajectory among the discrete states is found, it will replace the original trajectory for the next cycle. When the improved trajectory is applied to cascaded hydro plants, this multi-dimensional problem is generally decomposed into multiple one-dimensional problems by using dynamic programing successive approximation (DPSA) [29,36]. As a result, the cost of computing increases linearly with the number of stages since the problem is solved with two adjacent stages at a time.

As previously mentioned, the POA easily falls into the local optimum and is also sensitive to its initial solution. Therefore, the MSPOA is used to improve the quality of optimal solutions and enhance the convergence speed. The main idea of the MSPOA is that the initial solution is continuously optimized by relaxing the time-coupling constraints with a larger time step. The primary advantage of this method is that it is more efficient to find the optimal solution by converting the original STHS problem into a series of larger time step subproblems [9,33]. This method has been well applied in the China Southern Power Grid [33]. The MSPOA consists of the following steps, and a sketch map of the MSPOA is shown in Figure 2b.

1. Set the initial solution: The constant flow method is used as the initial solution, which the dashed lines denote in Figure 2b (I).
2. Set TI = 4 h by trail-and-error and TI is the time interval: The load and local flow of hydro plants in hourly intervals are transformed into the load and local flow in 4 h intervals by averaging the values. In this case, the time-coupling constraints, such as the power ramping constraint, are eliminated, and the number of computational stages is also reduced simultaneously. The output process from Step (1) is as the initial solution and the POA is used to obtain the optimal solution in 4 h intervals. The forebay level is taken as the state variable in the POA and a sketch map of the POA is shown in Figure 2a.
3. Set TI = 2 h: The solution (i.e., the power generation) from Step (2) is regarded as the initial solution in 2 h intervals, which the dashed lines denote in Figure 2b (II). The power ramping constraint is tightened compared to that of the 4 h intervals but is weakened compared to that of the hourly intervals. Then, the POA is used to obtain the optimal solution in 2 h intervals.
4. Set TI = 1 h: the solution from Step (3) is regarded as the initial solution in hourly intervals, which the dashed lines denote in Figure 2b (III). The constraints are the same as those in the original STHS problem at present. The optimal solution by using the POA is the result of the original STHS problem.

Figure 2. Sketch map of the multi-step progressive optimality algorithm (MSPOA). (a) The POA operation; (b) the operating process of the MSPOA.
3.3. Determining the Forebay Level and Output Under the Condition of Sensitive Expected Output

Two steps are involved in the calculation of the MSPOA: (1) determination of the output via the forebay level and (2) determination of the forebay level via the output. The calculation of the former is similar to the ordinary situation. However, the calculation of latter is slightly different from that for hydro plants, the expected output of which is insensitive. The calculation requires trials, and it is not easy to converge because of the sensitive expected output. An iterative approximation method is introduced to address this problem. The procedure of the method is described as follows, and a flow chart is shown in Figure 3.

1. Initialize \( q_{r,t} = \hat{Q}_{r,t} \) and \( \hat{p}_{r,t}, z_{r,t} \) are specified, where \( \hat{p}_{r,t} \) is the optimal solution of the problem with the larger time step.

2. Calculate \( z_{r,t+1}, h_{r,t} \) via Equations (4) and (6) and calculate \( p_{r,t}, \hat{p}_{r,t} \) via Equations (8) and (9).

3. Compare \( \hat{p}_{r,t} \) to \( \hat{p}_{r,t} \). If \( \hat{p}_{r,t} \) is greater than \( \hat{p}_{r,t} \), it violates the maximum output limit and update \( \hat{p}_{r,t} = (\hat{p}_{r,t} + \hat{p}_{r,t})/2 \). Then, go to Step (4).

4. Compare the difference between \( p_{r,t} \) and \( \hat{p}_{r,t} \). If the difference \( |p_{r,t} - \hat{p}_{r,t}| \) is larger than the specified convergence accuracy \( \varepsilon \), update \( q_{r,t} = \hat{p}_{r,t} / f'(h_{r,t}) \) and go back to Step (2). Otherwise, output \( p_{r,t}, q_{r,t}, z_{r,t+1} \).

![Figure 3. Flow chart of the iterative approximation method.](image)

3.4. Penalty Function

The reserve constraints are system-wide inequality constraints. They are hard to address if no additional process is introduced. It is a common method to use the penalty function to address system-wide inequality constraints in the POA and the improved algorithms of the POA. [37] Therefore, the reserve constraints are addressed by the penalty function in this study. Equations (14) and (15) are the up and down reserve penalty terms, respectively, where \( a_1 \) and \( a_2 \) are the penalty coefficients.

\[
F1 = \sum_{t=1}^{T} a_1 \left| \min_{r=1}^{R} \left( \hat{p}_{r,t} - p_{r,t} \right) - UIR_t, 0 \right|
\]
\[ F_2 = \sum_{t=1}^{T} \alpha_2 \min \left( \sum_{r=1}^{R} (p_{r,t} - \bar{p}) - DR_t, 0 \right) \]  

(15)

Water spillage is not allowed except when the forebay level exceeds its upper bound, so the spillage penalty term is introduced to reduce spillage in Equation (16). Equation (17) is the power ramping penalty term, which is only effective in hourly intervals.

\[ F_3 = \sum_{t=1}^{T} \sum_{r=1}^{R} \alpha_3 p_{r,t}^{spill} \]  

(16)

\[ F_4 = \sum_{t=1}^{T-1} \sum_{r=1}^{R} \alpha_4 \min(\Delta p_{r,t} - |p_{r,t+1} - p_{r,t}|, 0) \]  

(17)

where \( p_{r,t}^{spill} \) is the abandoned power via spilling, and \( p_{r,t}^{spill} = f_r(h_{r,t})s_{r,t} \).

3.5. Whole Solution Framework

On the basis of the abovementioned methods and strategies, Figure 4 shows the whole solution framework.

4. Case Study

4.1. Introduction of the Engineering Background

The Wujiang River is located in Guizhou Province in South China and is one of the thirteen hydropower bases in China. There are seven reservoirs in the main stream of the Wujiang River, and the total installed capacity reaches 8315 MW. The topological structure of the hydro plants is shown in Figure 5.

At the end of 2019, the wind and solar power capacities in Guizhou Province were 4570 MW and 5100 MW, respectively.
Typical planned and actual day-ahead wind power schedules are shown in Figure 6. The maximum difference between the planned and actual outputs is 1765 MW, and it lasts 5 h, as shown in Figure 6a. Figure 6b shows that the difference between the planned and actual output reaches −1567 MW. Therefore, the Guizhou Power Grid (GZPG) has to keep enough reserve to deal with the difference.

The objective is to perform peak shaving so that the coal-fired plants can maintain their unchanging unit commitment and generation over a long period. The up and down reserves are set to 2500 MW and 1800 MW, respectively, considering the schedule errors of wind and solar power in this province. The case is from the dry season, and the boundary conditions are listed in Table 2.

![Figure 5. Topological structure of the hydro plants in Wujiang River.](image)

![Figure 6. Typical day-ahead wind power schedules. (a) The planned output is greater than actual output; (b) the planned output is less than actual output.](image)

| Boundary Conditions          | HJD  | DF   | SFY  | WJD  | GPT  | SL   | ST   |
|------------------------------|------|------|------|------|------|------|------|
| Regulating ability           | Multi-yearly | Seasonally | Daily | Seasonally | Yearly | Daily | Daily |
| Initial forebay level (m)    | 1089.54 | 964.96 | 833.48 | 748.19 | 599.59 | 437.25 | 363.91 |
| Terminal forebay level (m)   | 1085.50 | 961.95 | 831.54 | 745.49 | 599.95 | 435.92 | 363.81 |
| Highest forebay level (m)    | 1140.00 | 970.00 | 837.00 | 760.00 | 626.24 | 440.00 | 365.00 |
| Lowest forebay level (m)     | 1076.00 | 936.00 | 822.00 | 720.00 | 590.00 | 431.00 | 353.50 |
| Installed capacity (MW)      | 600   | 695   | 600   | 1250  | 3000  | 1050  | 1120  |
| Minimum output (MW)          | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Maximum water discharge (m³/s) | 3866  | 11,142 | 15,956 | 18,360 | 23,560 | 25,737 | 27,500 |
| Minimum water discharge (m³/s) | 0     | 0     | 0     | 0     | 0     | 0     | 0     |
| Flow-time delay (h)          | 2     | 2     | 3     | 6     | 4     | 8     | 0     |
| Ramp rate (MW/h)             | 150   | 174   | 150   | 312   | 780   | 262   | 280   |

Table 2. Boundary conditions.
4.2. Results Analysis

The load, residual load, up reserve and down reserve are shown in Figure 7. Neither the up reserve nor the down reserve falls to the required minimum reserve, and there is no water spillage. The peak-valley difference between the original and residual loads decreases by 21.9%, from 6357 MW to 4963 MW. The standard deviation between the original and residual loads decreases by 34.4%, from 2042 MW to 1339 MW, representing a smoother load. These results illustrate that the method can achieve good performance for peak shaving. It can be inferred that the required reserve capacities are satisfied to balance the electrical perturbations from the wind and solar power during the time horizon. Here, the up reserve for each period is calculated by subtracting the hydropower generation from the expected output. The down reserve is calculated by summing the output generated by the cascaded hydro plants.

![Figure 7. The results of peak shaving with boundary conditions in Table 2.](image)

Figure 8 shows the outputs and the corresponding expected outputs of the hydro plants with the sensitive expected output. The expected outputs are less than the installed capacity. The average difference between the expected output and the installed capacity of GPT reaches 456 MW, and the total difference of the cascaded hydro plants reaches 728 MW. This high difference illustrates that the sensitive expected output has a pronounced effect on power generation and cannot be ignored in the generation schedules. Figure 8d also shows that the expected output of GPT fluctuates considerably over time. This is because the fluctuation of power generation causes the water discharge and tail water levels to vary greatly, and the expected output is sensitive to the net head. Appendix A Figures A1 and A2 show the power generation of the hydro plants with insensitive expected output, and the output can easily reach the installed capacity.
Figure 8. Generation schedules of expected output-sensitive plants with boundary conditions in Table 2. (a–d) are the generation schedules of HJD, DF, WJD and GPT, respectively.

The benefits of considering the sensitive expected output are shown by providing a similar conventional case that does not consider the impact of the sensitive expected output. In this case, the expected output equals the installed capacity. This comparison occurs while satisfying the same hydropower operational constraints. The results of the conventional case are shown in Figure 9. The comparison for the hydro system is summarized in Table 3. The introduced case denotes the solution considering the impact of the sensitive expected output while the conventional case denotes the solution without considering the impact.

Figure 9. The results of peak shaving without considering the sensitive expected output.
Table 3. Comparison of the results between the introduced and conventional case.

| Case         | Average Output (MW) | Standard deviation (MW) | Average Up Reserve (MW) |
|--------------|---------------------|-------------------------|-------------------------|
|              | HJD     | DF     | SFY    | WJD    | GPT    | SL     | ST     | Cascade Load | Residual Load | Reduction Ratio (%) |
| Introduced   | 279     | 446    | 315    | 683    | 1105   | 559    | 604    | 3991    | 2042     | 34.4   | 3592   |
| Conventional | 279     | 447    | 319    | 727    | 1170   | 590    | 634    | 4166    | 2042     | 44.1   | 4149   |

The total average output of the introduced case is 3991 MW, which is less than the 4166 MW of the conventional case. The standard deviation of the residual load is greater than the result of the conventional case. The reason for the difference may be that the output of the introduced case can only reach the expected output, while the output of the conventional case can reach the installed capacity. In other words, the output fluctuation range of the introduced case is less than that of the conventional case, which means that the feasible region has been narrowed compared to that of the conventional case.

Comparing the outputs of the hydro plants, as shown in Figures 8 and 10, it is obvious that the outputs of DF and WJD in the conventional case reach the installed capacity at certain periods. The corresponding expected outputs are less than the installed capacity according to the introduced case, which means that the outputs exceed the upper bound at certain periods, and this situation has no chance to occur in practice. This situation further causes the calculated up reserve to be inaccurate, and the up reserve may not be sufficient for renewable power fluctuations because the expected output is overestimated in the conventional case.

![Figure 10](image-url) Generation schedules of plants without considering the sensitive expected output. (a–d) are the generation schedules of HJD, DF, WJD and GPT, respectively.
In a word, the application of the MSPOA for hydro plants with the sensitive expected output can meet the peak shaving demands. The obtained hydropower schedules are more accordant with practical circumstances, and the up reserve is more accurate so that it can cope with renewable power fluctuations effectively. The sensitivity analysis of the initial solution is considered. The uniform decline of the forebay level is taken as the initial solution and the obtained standard deviation of the residual load is 1355 MW. The result is near the introduced case and it indicates that the effect of the initial solution on peak shaving is very small. It should be noted that the sensitive expected output effect is less significant in the wet season because the net head is high and the expected output is equal to the installed capacity. Hydro units are usually running at full power generation and hydro plants are no longer responsible for peak shaving in the wet season so that the water resources can be fully used to generate power. The model was developed and implemented in Python 3.6 and tested on a laptop with the following configuration: Intel(R) Core(TM) i5-6300HQ CPU @ 2.30 GHz with 4 logical processors and 16.0 GB RAM. The solution was obtained in less than 45 min, and it is acceptable for an STHS problem with a time horizon of 7 days.

5. Conclusions

The model developed in this study takes into consideration the sensitive expected output of hydro plants in the STHS, which provides reserve services to cope with renewable power fluctuations. The MSPOA is used for the STHS problem, and an iterative approximation method is proposed to determine the forebay level and output under the condition of the sensitive expected output. The case study is illustrative of the advantages of the model in terms of peak shaving. Compared with not considering the sensitive expected output effect, a major advantage of our approach is to consider the effect so that the obtained hydropower schedules are more accordant with practical circumstances and the up reserve is more accurate to cope with renewable power fluctuations. The proposed approach is both accurate and computationally acceptable, providing better results for expected output-sensitive cascaded hydro systems.

Author Contributions: R.Z. carried out the study design, the experimental work, the analysis and interpretation of data and drafted the manuscript; C.C. participated in the study design, data collection, analysis of data and preparation of the manuscript; S.L. participated in the design and coordination of the experimental work, and acquisition of data; Z.Z. participated in the experimental work, the data collection and interpretation. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Figure A1. Generation schedules of expected output-insensitive plants with boundary conditions in Table 2. (a–c) are the generation schedules of SFY, SL and ST, respectively.
Figure A2. Generation schedules of other plants in Wujiang River without considering the sensitive expected output. (a–c) are the generation schedules of SFY, SL and ST, respectively.

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