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Optimal Operation of Interprovincial Hydropower System Including Xiluodu and Local Plants in Multiple Recipient Regions

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Received: 15 October 2018; Accepted: 31 December 2018; Published: 2 January 2019

Abstract: This paper focuses on the monthly operations of an interprovincial hydropower system (IHS) connected by ultrahigh voltage direct current lines. The IHS consists of the Xiluodu Hydropower Project, which ranks second in China, and local plants in multiple recipient regions. It simultaneously provides electricity for Zhejiang and Guangdong provinces and thus meets their complex operation requirements. This paper develops a multi-objective optimization model of maximizing the minimum of total hydropower generation for each provincial power grid while considering network security constraints, electricity contracts, and plant constraints. The purpose is to enhance the minimum power in dry season by using the differences in hydrology and regulating storage of multiple rivers. The TOPSIS method is utilized to handle this multi-objective optimization, where the complex minimax objective function is transformed into a group of easily solved linear formulations. Nonlinearities of the hydropower system are approximatively described as polynomial formulations. The model was used to solve the problem using mixed integer nonlinear programming that is based on the branch-and-bound technique. The proposed method was applied to the monthly generation scheduling of the IHS. Compared to the conventional method, both the total electricity for Guangdong Power Grid and Zhejiang Power Grid during dry season increased by 6% and 4%, respectively. The minimum monthly power also showed a significant increase of 40% and 31%. It was demonstrated that the hydrological differences between Xiluodu Plant and local hydropower plants in receiving power grids can be fully used to improve monthly hydropower generation.

Keywords: interprovincial hydropower system; multiple power grids; multi-objective; mixed integer nonlinear programming (MINLP); polynomial formulations

1. Introduction

A hydropower reservoir that often has large storage capacity is capable of scheduling the generation on a time scale. The optimal operation of such a hydropower reservoir aims to improve the generation policy for production maximization or other purposes [1]. For a multiple-reservoir cascaded hydropower system, the coordination among the reservoirs can create additional opportunities to further improve their operational policies [2]. When multiple cascaded hydropower systems on different rivers are connected by a power network, the joint operation provides great potential for increasing cooperative generation production of the entire system using the complementarities of hydrology, storage capacity, and generation capacity. However, this problem exhibits more complexity

because of many time and space coupled constraints and different electrical demands from multiple power grids. The present study tackles such a problem, which originates from actual operations of China's hydropower system.

China has been experiencing an unprecedented hydropower boom since implementing the national project "Electricity Transmission from West to East" in 2000 [3]. During this period, many hydropower-rich rivers in the southwest region were extensively exploited, such as Jinsha River, Lancang River, Yalong River, Dadu River, Hongshui River, and Wujiang River. On the main streams, a batch of large hydropower plants with 600 MW or bigger generating units as well as large storage have been put into operation or are still under construction [4]. Because of a locally underdeveloped economy, the major part of electricity from these plants is transmitted to load centers in eastern and coastal China via ultrahigh voltage direct current (UHVDC) lines. In particular, some large hydropower projects need to simultaneously undertake the electric supply for multiple regions or provinces [5,6]. For example, the famous Three Gorges Project is connected to three big regional power grids to serve their subordinate provinces. Another example is the Xiluodu Hydropower Project (XHP), which provides electricity for Guangdong province in the southern region and Zhejiang province in the eastern region. Through the nationwide electricity transmission network, the large hydropower plants in southwest China have been widely connected with those in recipient regions and provinces, and thus interprovincial hydropower systems (IHSes) are formed [7].

The optimal operation of an IHS is a challenging task that exhibits great complexity compared to conventional cascaded hydropower plants. An IHS is required to meet complex electricity needs of multiple recipient power grids that have greatly different load characteristics and operation requirements [8]. This makes it difficult to choose suitable optimization models. While transmitting power via a UHVDC network, moreover, network security boundaries and system conditions such as transmission capacity limitations and energy control targets must be considered. These constraints are stringent and thus bring much difficulty with regard to the optimal operations of an IHS. Besides, an IHS is composed of several groups of hydropower plants located in different rivers or provinces. There usually exist different runoff characteristics among these groups due to great differences in geography, weather, and hydrology. A typical example is the XHP in Jinsha River and local hydropower plants in Zhejiang Province. The XHP enters the main flood period in July and ends in September, during which the monthly inflows are far larger than the annual average. In contrast, the main flood season of Qiantang River is from March to September, especially from April to June. Such differentiated hydrological characteristics provide opportunities and challenges to implement the coordinated operations of hydropower plants. Appropriate models and methods are needed.

Hydropower optimization considering multiple power grids or network security constraints has attracted more and more research. Cobian solved an optimal scheduling of one pump-storage plant in combination with several interconnected power systems [9], but the used objective of minimizing total operating costs was greatly different from that of the current problem. In addition, the hydraulic connection between cascaded hydropower plants was not involved in the study. Shen et al. [10], Cheng, et al. [8], Feng et al. [11], and Lu et al. [12] focused on the short-term peak shaving operation of multiple power grids. They developed some specific methods and strategies to allocate power generation among power grids, but ignored network security constraints. Norouzi et al. [13] considered direct current (DC) power flow equations and transmission flow limits in hydro/thermal unit commitment. They modeled the network security constraints as linear constraints. Johannesen et al. [14] also presented optimal hydro scheduling including security constraints. This study decomposed the original problem into a hydro subproblem and an electrical subproblem, and dealt with the stability constraints by a special linear programming technique. These two previous works were demonstrated by respective case studies involving a single power grid. When applied to the coordinated operations of multiple power grids, the optimization models and methods may be unsuitable. Besides, hydropower operation coupled with other variable renewable sources such as solar and wind is another important work. Much research has taken advantage of

the generating complementarity among different power sources to improve the operation policies of hydropower plants or to smooth the integration of solar energy into the power system [15–17]. These works provided additional insight into the generation operation of a complex interconnected system.

Mathematically, the present problem is a high-dimensional, nonlinear, multistage, and multi-objective optimization [18]. In the past decades, three kinds of techniques have been developed for this problem: Mathematical programming [19,20], dynamic programming (DP) and a DP-based method [21–23], and population-based algorithms [24–26]. In mathematical programming, linear programming and nonlinear programming methods are widely used. They commonly require linear approximation of nonlinear curves and relationships of the hydropower system, or redescription of the original problem, in order to meet the computable requirements of the commercial software. It may take a high amount of effort to guarantee high accuracy in optimization. The DP-based methods are also popular, but face calculation difficulties as the computational time and memory requirements increase exponentially with the number of hydropower plants and discrete states [27]. The population-based algorithms are hard to provide stable solutions for hydropower systems in practice, which may seriously restrain wide use of these techniques. The advantages and disadvantages of these optimization techniques have been successively reviewed in the literature [28–31]. In addition, such a multi-objective optimization requires a suitable way. Two main ways are usually utilized. One is to combine multiple objectives by using a weighting method, constrained method, or other methods [32,33]. The other is to solve directly the original multi-objective optimization problem using multi-objective optimization algorithms such as the nondominated sorting genetic algorithm II [34,35]. It is generally agreed that the choice of optimization method should depend on the characteristics of the considered hydropower system and the actual requirements.

In this paper, a multi-objective optimization model of maximizing respective minimum power for multiple provincial power grids is developed. This model considers network security constraints and electricity contracts, as well as plant operation limitations in water level, power, and discharge. The main purpose is to enhance the power supply in dry season by using differences in hydrology and regulating the storage of multiple rivers. This multi-objective optimization is handled by the TOPSIS method, where the complex minimax objective function is transformed into a group of linear formulations. Moreover, nonlinearities of the hydropower system are approximatively described as polynomial formulations so that the model is efficiently solved. The developed model was verified by optimizing the monthly generation schedules of the IHS that consists of XHP and local hydropower plants in Guangdong and Zhejiang provinces. Furthermore, it was compared to the commonly used energy production maximization model while considering the same input data.

The rest of this study is organized as follows. Section 2 describes XHP and the IHS in detail. The optimization model, including objective function and constraints, is presented in Section 3, and correspondingly the solution method is given in Section 4. In Section 5, the application of the developed model to the IHS is analyzed and discussed, and a comparison with the conventional method is given. Section 6 concludes the study.

2. Xiluodu Hydropower Project

The XHP is located in the downstream of the Jinsha River, which is the upper stretch of the Yangtze River. The plant has 18 identical hydropower units of 700 MW, which are equally installed in its left and right sides. Its total installed capacity ranks second in China and third in the world. As one of the main power suppliers of the “Electricity Transmission Project from West to East”, generating units of the plant in the left and right bank respectively provide electricity for Zhejiang via the Binjin UHVDC line and for Guangdong province via the Niucong UHVDC line. Correspondingly, it is simultaneously operated by two different dispatching departments, the China Southern Grid (CSG) and the State Grid Corporation of China (SGCC). In flood season, most hydropower plants, especially small-sized ones in Yunnan, commonly face spillage risk. Local electricity demands can be easily satisfied. To reduce spillage water, some large hydropower plants, such as XHP, need to transmit all their electricity to

load centers in eastern and coastal China via a UHVDC. According to the multilateral contracts, 50% of generation production from Xiluodu is transmitted to Zhejiang Power Grid (ZJPG) in SGCC and the other to Guangdong Power Grid (GDPG) in CSG. In contrast, during dry season, small-sized hydropower plants can barely satisfy local electricity demands because of low inflow. In this case, the XHP is also responsible for the power supply of Yunnan and Sichuan provinces, except serving Zhejiang and Guangdong provinces.

Through the UHVDC power network, the XHP is connected with many remote hydropower plants located in the above recipient provinces. All of these plants constitute an interprovincial hydropower system, as shown in Figure 1. In the IHS, Fengshuba and Xinfengjiang are dispatched by GDPG and the other seven hydropower plants by ZJPG. In other words, the IHS is managed by four dispatching departments and needs to meet the complex operation requirements of multiple power grids. Because they are separately dispatched, the operation schemes of these hydropower plants often have difficulty reflecting efficient, or even suitable, operation decisions. Hence, there is a need for the coordinated operation of these plants located in different provinces, which can give full play to their different characteristics in hydrology, generation capacity, regulating storage, and other factors (see Tables 1 and 2) to meet discrepant requirements of multiple power grids.

Figure 1. Structure diagram of interconnected hydropower system.

Table 1. Characteristics of Xiluodu Hydropower Project (XHP).

Installed Capacity (MW)	Regulating Ability	Normal Level (m)	Dead Level (m)	Flood Control Level (m)	Flood Season (Main Flood Season)
13,860	Quarterly	600.00	540.00	560.00	June to October (July to September)

Table 2. Characteristics of hydropower plants in Zhejiang and Guangdong provinces.

Hydropower Plant	Regulating Ability	Installed Capacity (MW)	Normal Level (m)	Dead Level (m)	Flood Season (Main Flood Season)
Shanxi	Multi-yearly	200	142.00	117.00	March to October (April to June)
Tankeng	Yearly	604	160.00	120.00	
Jinshuitan	Yearly	305	184.00	164.00	
Shitang	Daily	85.8	102.50	101.10	
Sanxikou	Daily	99.9	18.00	17.75	
Hunanzen	Yearly	320	230.00	190.00	April to September (May to July)
Huangtankou	Daily	88	115.00	114.00	
Fengshuba	Yearly	180	166.00	128.00	
Xinfengjiang	Multi-yearly	335	116.00	193.00	

3. Problem Formulation

3.1. The Objective Function

This paper utilizes the objective of maximizing the minimum monthly power from the hydropower system. The main purpose is to enhance the power supply of each grid in dry season [36] by use of the coordinated operations of Xiluodu and local hydropower plants in recipient regions. For any power grid, the objective can be formulated as

$$\begin{cases} \text{Max } F_g \\ F_g = \text{Min} \sum_{1 \leq t \leq T_i=1}^I p_{i,g,t} \end{cases} \quad (1)$$

Obviously, this is a multi-objective optimization that contains G objectives. That is to say, the number of objectives is equal to the number of the power grids. In the present study, two power grids are considered.

3.2. Constraint Conditions

3.2.1. System Constraints

- Network security constraint:

$$p_{i,g,t} \leq P_{l,t} \quad (2)$$

This constraint represents the limitation of power transmission via a UHVDC line.

- Energy target in flood season:

$$\sum_{t \in \Omega} p_{i,g,t} \times \Delta t = E_i^{\Omega} \times r_{i,g}^{\Omega} \quad (3)$$

The constraint is dependent on the specified rate of electricity allocation in flood season.

- Energy target in dry season:

$$\sum_{t \in \Phi} p_{i,g,t} \times \Delta t = E_i^{\Phi} \times r_{i,g}^{\Phi} \quad (4)$$

Similarly, the constraint is dependent on the specified rate of electricity allocation in dry season.

- Power balance for each plant:

$$\sum_{g=1}^G p_{i,g,t} = p_{i,t}, \quad t = 1, 2, \dots, T. \quad (5)$$

With this constraint, the sum of power transmitted to each grid is equal to the power generation of the plant.

3.2.2. Plant Constraints

- Water balance:

$$V_{i,t+1} = V_{i,t} + (I_{i,t} - Q_{i,t} - q_{i,t}) \times \Delta t. \quad (6)$$

The above equation ensures that total inflow and outflow are balanced between cascaded hydropower plants.

- Specified target demand for reservoir storage:

$$V_{i,T} = V'_{i,T} \quad (7)$$

This is the demand for storage at the end of the time horizon. The constraint is satisfied when the deviation $|V_{i,T} - V'_{i,T}|$ is less than the specified accuracy.

- Minimum and maximum turbine discharge for each hydro plant:

$$\underline{Q}_{i,t} \leq Q_{i,t} \leq \overline{Q}_{i,t} \quad (8)$$

The constraint is related to available turbine units.

- Minimum and maximum discharges for each reservoir:

$$\underline{S}_{i,t} \leq S_{i,t} \leq \overline{S}_{i,t} \quad (9)$$

The lower boundary is usually set according to the downstream flow requirement, while the upper is determined by the flood control requirement.

- Minimum and maximum reservoir storage:

$$\underline{V}_{i,t} \leq V_{i,t} \leq \overline{V}_{i,t} \quad (10)$$

This constraint means that reservoir level at the end of period t is limited within a reasonable range.

- Minimum and maximum power:

$$\underline{p}_{i,t} \leq p_{i,t} \leq \overline{p}_{i,t} \quad (11)$$

The upper bound of power depends on available generating capacity, while the lower bound on the minimum technical output of all turbine units.

3.2.3. Plant Conditions

- Relationship between forebay level and reservoir storage:

$$Z_t = f_{zv}^i(V_t) \quad (12)$$

The relationship indicates that forebay level is a function of reservoir storage.

- Relationship between tailrace water level and reservoir discharge:

$$Zd_t = f_{zd}^i(S_t) \quad (13)$$

Here, the tailrace water level is assumed to be dependent on the reservoir discharge.

- Relationship between penstock loss and turbine discharge:

$$h_t^{loss} = f_{loss}^i(Q_t) \quad (14)$$

It should be noted that the penstock loss is usually calculated using the unit discharge.

- Relationship between energy production efficiency and net head:

$$\begin{cases} \xi_{i,t} = f_{wrh}^i(h_t) \\ h_{i,t} = \frac{(Z_{i,t} + Z_{i,t-1})}{2} - Z d_{i,t} - h_{i,t}^{loss} \end{cases} \quad (15)$$

where $h_{i,t}$ denotes the net head, which is obtained by subtracting penstock loss from the gross head. This relationship shows that the energy production efficiency varies with the net head of the plant.

- Hydropower production function:

$$p_{i,t} = 3.6 \times \xi_{i,t} \times Q_{i,t} \quad (16)$$

The average power during each period is calculated by the above equation.

4. Problem Solution

4.1. Solving the Multi-Objective Optimization

The TOPSIS method [37] is used to convert the multi-objective optimization to a single-objective one. It consists of two steps. In the first step, the optimal solution of each objective function is obtained. The second step reconstructs a new objective function to make each objective value gradually approximate the best solution during the optimization process. Based on Equation (1), the reconstructed objective function can be represented as

$$\begin{cases} \min F \\ F = \sum_{g=1}^G (F'_g - F_g^*)^2 \end{cases} \quad (17)$$

where F_g^* denotes the optimal solution of the objective function for power grid g , which is obtained from the corresponding single-objective optimization problem. F'_g denotes the calculated objective value during the optimization process, described in the next subsection.

4.2. Solving Minimax Optimization

As we see from Equation (1), the original objective function is a complex minimax formulation. Mathematically, this type of objective is disadvantageous to solve. In previous literature [38,39], such an objective function was usually transformed into an aggregate function. However, this approach requires a highly accurate parameter value that represents the solution precision. Determining this parameter is a difficult task because it has an enormous impact on the convergence of the algorithm and the optimization results. Therefore, this paper uses an approach that introduces a group of formulations to equivalently substitute the original objective function. In this way, the objective can be rewritten as Equations (18)–(19):

$$\max F'_g = P_{g,\min} \quad (18)$$

Subject to:

$$\begin{aligned} \sum_{i=1}^I p_{i,g,t} &\geq p_{g,\min} \\ t &= 1, 2, \dots, T \\ g &= 1, 2, \dots, G \end{aligned} \quad (19)$$

The above objective function is advantageous to solve. Besides, these new linear constraints can also be easily handled.

4.3. Reformulating Nonlinearities of the Hydropower System

Hydropower system operations involve complex nonlinearities, such as the relationships between forebay level and storage, tailrace level and discharge, as well as energy production efficiency and net head. The formulation of these nonlinearities usually depends on the requirements of the used optimization method. This paper employs the mixed integer nonlinear programming (MINLP) technique to retain the original characteristics of hydropower systems as far as possible. In MINLP, the polynomial technique is employed to reformulate the nonlinearities of a hydropower system.

As can be seen from Equation (16), power generation is related to turbine discharge and energy production efficiency. The latter depends on the net head, which is a function of forebay level, tailrace level, and penstock loss. The forebay level is determined by the initial and ending storage of the reservoir at each period. It can be calculated through the relationship between forebay level and storage. In an MINLP model, this relationship is usually linearized piecewise [40]. With the present MINLP, the forebay level is described as a quartic polynomial of water volume, shown as follows:

$$Z_{i,t} = a_{i,0} + a_{i,1}V_{i,t} + a_{i,2}V_{i,t}^2 + a_{i,3}V_{i,t}^3 + a_{i,4}V_{i,t}^4, \quad (20)$$

where $a_{i,0}, a_{i,1}, a_{i,2}, a_{i,3}, a_{i,4}$ denote coefficients dependent on the curve of the forebay level and reservoir storage. Here, the quartic polynomial was fitted by Matlab 2014R. This formulation presents high accuracy between the fitted data and real data, according to the test of hydropower plants in the later case study. For example, the deterministic coefficient R^2 of the XHP reached 0.9999. Other plants also showed high accuracy, with more than 0.95.

The tailrace level, which is a function of total reservoir discharge, is also represented by using the polynomial technique. To obtain a high-accuracy polynomial, we compared several fitted functions with different orders for the considered hydropower plants. Consequently, the fourth-order polynomial in terms of total discharge was most accurate, expressed as Equation (21). It should be noted that the type of polynomial that is more suitable depends on the real data of the specified hydropower plants. Besides, in some cases there may exist hydraulic coupling between some plants located on a single river. This means the tailrace level of the upstream plant is also affected by the forebay level of the immediate downstream reservoir. This paper mainly takes into account the usual situation. The special situation with hydraulic coupling will be involved in a future study. Here,

$$Zd_{i,t} = b_{i,0} + b_{i,1}S_{i,t} + b_{i,2}S_{i,t}^2 + b_{i,3}S_{i,t}^3 + b_{i,4}S_{i,t}^4, \quad (21)$$

where $b_{i,0}, b_{i,1}, b_{i,2}, b_{i,3}, b_{i,4}$ are coefficients dependent on the relationship between tailrace level and release water. Besides, the penstock head loss is usually modeled as a quadratic function of the turbine discharge. Here, the penstock loss coefficient c_i and constant c'_i of plant i needs to be considered. Thus, this function can be formulated as

$$h_{i,t}^{loss} = c_i Q_{i,t}^2 + c'_i \quad (22)$$

With the above Equations (20)–(22), the net head function can be rewritten as a fourth-order polynomial of storage volume, turbine discharge, and spillage, shown in (23):

$$h_{i,t} = a_0 - b_0 - c'_i - \left(S_1 q_{i,t} + S_2 q_{i,t}^2 + S_3 q_{i,t}^3 + b_4 S_{i,t}^4 \right) - c_i Q_{i,t}^2 + 0.5 \left(a_1 (V_{i,t} + V_{i,t-1}) + a_2 (V_{i,t}^2 + V_{i,t-1}^2) + a_3 (V_{i,t}^3 + V_{i,t-1}^3) + a_4 (V_{i,t}^4 + V_{i,t-1}^4) \right) \quad (23)$$

To calculate the power generation in the optimization procedure, the $f_{wrh}^i(\cdot)$ is also reconstructed as a polynomial function of net head, which is the following equation:

$$\xi_{i,t} = d_{i,0} + d_{i,1}h_{i,t} + d_{i,2}h_{i,t}^2 + d_{i,3}h_{i,t}^3 + d_{i,4}h_{i,t}^4, \quad (24)$$

where $d_{i,0}, d_{i,1}, d_{i,2}, d_{i,3}, d_{i,4}$ are the fitted coefficients.

4.4. Optimization Method

The method used in this study is based on the branch-and-bound technique, which is capable of implementing global optimization [41]. The core idea is to exhaustively search over all subproblems for convergence to the global solution. The optimization procedure for the present problem is summarized as the following steps:

- **Step 1.** Set the initial objective function value f^* as positive infinity;
- **Step 2.** Put the original problem on the list to be solved;
- **Step 3.** Get one problem from the list. Here, the optimization search will stop until the list is empty;
- **Step 4.** Generate a convex relaxation of the function included in the current problem and then solve the relaxed convexified model. In this step, several mathematical techniques including convexification, linearization, interval analysis, preprocessing, constraint propagation, and algebraic reformulation are employed;
- **Step 5.** If there is no feasible solution for the relaxed problem, then go back to Step 3;
- **Step 6.** If the obtained solution is no smaller than the current objective value f^* , then go back to Step 3;
- **Step 7.** If this solution of the relaxed problem is not feasible for the current problem, or if the objective values of the two problems are not the same, then go to Step 9. Otherwise, go to Step 8;
- **Step 8.** Set f^* equal to the calculated objective value if f^* is bigger than it, and then go to back Step 3;
- **Step 9.** Split the feasible region of the current problem into two parts that represent two new subproblems. Put them both on the list and go back to Step 3.
- The above procedure is a whole solution framework. Details are available from Reference [38].

5. Case Study

5.1. Input Data

The proposed method was verified as a case of the optimal operation of the IHS described in Section 2. This case focused on determining monthly generation schedules of all hydropower plants according to the real-world operation requirements of GDPG and ZJPG. The input data of the optimization model mainly came from actual operation records. The allocation proportions of energy production from Xiluodu are different in the flood season and dry season, as listed in Table 3. As we see, in dry season, only 70% of the total generation is transmitted to GDPG and ZJPG. That is because another 30% is used to satisfy the local electricity needs in Yunnan and Sichuan provinces. The maximum transmission capacities of Niucong and Binjin UHVDC lines are 6400 MW and 8000 MW. It should be mentioned that all the basic characteristic parameters and curves of each plant, as well as hydrological data, came from the dispatching centers of China Southern Power Grid and Zhejiang Power Grid. In particular, the inflow data of all hydropower plants was set to a statistical average of historical records over several decades. This data should be updated with the forecasted inflows that are usually obtained from runoff prediction systems, while applying the present method to the actual operations.

Table 3. Allocation rate of energy production from Xiluodu hydropower plant. ZJPG: Zhejiang Power Grid; GDPG: Gongdong Power Grid.

Flood Season (June to October)		Dry Season	
ZJPG 50%	GDPG 50%	ZJPG 35%	GDPG 35%

The considered IHS involves three dispatching apartments that respectively schedule their own hydropower plants. Usually, each of them just considers their own operation requirements in practice, and thus the coordination among different groups of hydropower plants is ignored. To obtain practical and efficient generation schedules, this paper took into consideration the coordinated operations of the IHS. The optimized operation schemes using the present model are described and analyzed in the next subsection. A comparison to the conventional optimization model with an energy production maximization objective is given in Section 5.3 to validate the practicability and efficiency of the present method.

Besides, it should also be mentioned that hydropower satisfies only a part of electricity demands in the recipient provinces. This study focuses on hydropower optimization, aiming at enhancing the electricity of a hydropower system during dry season to bear responsibility for power supply and peak response for power grids. With optimized monthly generation, the coordination between hydropower and coal-fired plants can be carried out in daily and hourly operations and unit commitment.

5.2. Analysis of the Optimized Operation Schemes

This subsection presents elaborate analysis about optimized operation schemes to test and verify the effectiveness and rationality of the developed method. Figures 2 and 3 respectively give the power generation of Xiluodu and its allocation between two power grids, as well as the forebay level change over the entire time horizon. Figure 4 shows the forebay level profiles and generation profiles of other hydropower plants. In these figures, the maximum level was respectively set as normal reservoir level in dry season and flood control level in flood season, which was dependent on common requirements in the reservoir operation and management of China. The total monthly hydropower generations transmitted to ZJPG and GDPG are depicted in Figures 5 and 6, respectively.

Figure 2. Power generation produced from Xiluodu and its allocation between two power grids.

Figure 3. Forebay level profile of Xiluodu.

It is generally agreed that, in long-term operations, the emphasis of analyzing the optimized schemes should be placed on the forebay levels of large reservoirs and monthly generation schedules. The reason is that these reservoirs play a dominant role in regulating the allocation of inflow. As can be observed from the optimized results, all of the reservoir plants worked at available levels during the entire operational horizon. The forebay levels in Xiluodu decreased close to its dead level of 540.00 m before flood season so that more storage capacity was left for the later floods. In this case, 72% of its generation (about 2416 GWh) was produced from June to October. Moreover, the hydropower was conveyed at nearly maximum transmission capacity to GPDG and ZJPG in order to cover the electricity shortage in summer. In contrast, the local regulating reservoirs in recipient provinces generated much power before July. For instance, Tankeng, which is the largest hydropower plant in ZJPG, provided 68% of its total electricity production from January to April. Correspondingly, this reservoir operated at relatively low forebay levels in this period. Xinfengjiang in GPDG worked with its installed capacity during the prior six months, except May. As a result, such operation schedules helped the recipient power grids effectively improve the power supply in dry season. The result was in keeping with the optimization objective. Thus, it can be inferred that the hydrology differences between Jinsha River and other rivers were fully considered in the present operation schemes. It was also demonstrated that the coordinated operation of such an IHS is feasible and significant.

Figure 4. Cont.

Figure 4. Cont.

Figure 4. (a) Generation and forebay level profiles of Shanxi; (b) Generation and forebay level profiles of Tankeng; (c) Generation and forebay level profiles of Jinshuitan; (d) Generation and forebay level profiles of Shitan; (e) Generation and forebay level profiles of Sanxikou; (f) Generation and forebay level profiles of Hunanzhen; (g) Generation and forebay level profiles of Huangtankou; (h) Generation and forebay level profiles of Fengshuba; (i) Generation and forebay level profiles of Xinfengjiang.

Besides, we can see from Figures 5 and 6 monthly generation schedules, especially the electricity distribution in dry season and flood season for each power grid. Obviously, the majority of the electricity supply occurred from June to October. That is because both provincial power grids receive much hydropower from Xiluodu. It was indicated that the hydropower from southwest China had a big share in recipient power grids and could make an important effect on their operations. In dry season, the minimum hydropower generations reached 1868 MW in GDPG and 2064 MW in ZJPG, respectively. Moreover, the values remained unchanged in each month, which implies the minimum power was enhanced to an extreme. It should be noted that Xiluodu contributed more to this result than local hydropower plants. The average shares in GDPG and ZJPG were 85% and 77%, respectively. Therefore, it is necessary for recipient provinces to give more attention to the operations of the outer large hydropower plants.

Figure 5. Total hydropower generation of ZJPG.

Figure 6. Total hydropower generation of GDPG.

5.3. Comparison to Conventional Optimization Model

A comparison between the monthly operation results from our method and those from the conventional optimization model is shown in this subsection. As seen from Tables 4 and 5, there were obvious differences in the monthly average power between the two methods. Our model gave more electricity production during the dry season than the conventional model did. Specifically, the minimum hydropower generation from our model in dry season respectively increased 40% in ZJPG and 31% in GDPG. The average power also showed a respective increase of 6% and 4% in the

two power grids. In other words, the increased electricity during dry season amounted to 558 GWh and 323 GWh. The results indicate that the abundant hydropower was effectively transferred from flood season to dry season using hydrology differences and regulating storage differences. It was also implied that optimizing hydropower allocation between the two power grids was quite useful, while fixing the respective total electricity in dry season or flood season.

Table 4. The monthly power of Zhejiang Power Grid. Unit: MW.

Month	The Present Model			Conventional Optimization Model		
	Hydropower from XHP	Hydropower from Local Plants	Total Generation	Hydropower from XHP	Hydropower from Local Plants	Total Generation
1	580	1484	2064	1278	227	1505
2	1889	175	2064	1278	195	1473
3	1680	384	2064	1278	392	1670
4	1640	424	2064	1278	684	1962
5	1565	499	2064	1756	866	2622
6	4253	336	4589	4147	651	4798
7	5695	324	6019	6300	534	6834
8	6300	187	6487	6300	596	6896
9	6300	182	6482	6300	306	6606
10	5714	169	5883	6300	169	6469
11	1912	152	2064	2464	195	2659
12	1884	180	2064	1557	209	1766

Table 5. The monthly power of Guangdong Power Grid. Unit: MW.

Month	The Present Model			Conventional Optimization Model		
	Hydropower from XHP	Hydropower from Local Plants	Total Generation	Hydropower from XHP	Hydropower from Local Plants	Total Generation
1	1496	372	1868	1278	150	1428
2	1452	415	1867	1278	177	1455
3	1518	350	1868	1278	273	1551
4	1353	515	1868	1278	506	1784
5	1653	215	1868	1756	515	2271
6	2815	442	3257	4147	515	4662
7	6300	120	6420	6300	280	6580
8	6300	50	6350	6300	140	6440
9	6300	120	6420	6300	171	6471
10	6300	50	6350	6300	101	6401
11	1805	63	1868	2464	57	2521
12	1818	50	1868	1557	53	1610

According to the comparisons shown in Figures 3, 4, 7 and 8, we further analyzed the operations of Xiluodu and local hydropower plants. It can be observed that Xiluodu's operation schemes from different optimization models showed obvious changes in terms of the monthly generation. The conventional model produced 26% of its energy production in dry season and 74% in flood season. In contrast, the first share increased to 28% and the second decreased to 72% using the present model. The electricity transfer just reflected the difference in optimization objectives used in the two models. This implies that the present objective effectively enhanced the power supply of the hydropower system in dry season by losing the generation efficiency. For the local hydropower plants, larger changes in operation schedules occurred. While using the conventional model, these hydropower plants commonly operated at the maximum level for most periods to enhance generation efficiency. Shanxi and Tankeng in ZJPG, as well as Fengshuba and Xinfengjiang in GDPG, were typical examples. When choosing the present model, in contrast, the forebay levels of these plants in dry season decreased substantially. For example, Tankeng always worked at about 135.00 m from February to May, far lower than the maximum level of 160.00 m. In Xinfengjiang reservoir, there was also a rapid descent in the forebay level before flood season. The average monthly decrease approximated 3 m, which was twice that obtained from the conventional model. The forebay levels of Hunanzhen reservoir in Figure 4f also decreased substantially in dry season to enhance the power generation, fully

using their large storage. Additionally, reservoir levels had little effect on the monthly operations of Sanxikou and Huangtankou because both plants are daily regulation with small storage. In long-term planning operations, this type of plant actually generates a fixed level. The results indicated that the local hydropower plants were required to provide more generation output in dry season while implementing the coordinated operations. The shortage of the electricity supply in flood season was satisfied by Xiluodu. It was also demonstrated that the present optimization model achieved effective coordination between Xiluodu and local hydropower plants.

Figure 7. Power generation produced from Xiluodu and its allocation using the conventional method.

Figure 8. Comparison of power generation from Xiluodu between the two methods.

6. Conclusions

In China, many complex interconnected hydropower systems through UHVDC lines are facing operation challenges. The electricity transmission project of Xiluodu-ZJPG and -GDPG is seen as representative of such interconnected hydropower systems. This study described in detail the hydropower project characteristics and operation requirements and difficulties. Based on a real-world situation, a multi-objective optimization model maximizing the minimum power of multiple power grids was developed for the coordinated operations of Xiluodu and local hydropower plants in these receivers. An optimization method that integrates several strategies and the MINLP technique was also proposed to solve the model. The developed model was verified by a case study using actual operations data. An elaborate analysis about the optimized operation schemes and a comparison to

the conventional optimization model were given and discussed. The conclusions are summarized as follows:

- (1) The proposed method can make full use of hydrological differences to transfer hydropower energy from flood season to dry season, and effectively increases electricity and enhances minimum power in dry season of the two receiving power grids compared to the conventional optimization model of energy production maximization;
- (2) Compared to the conventional method, which allocates power generation in each month using fixed ratios, optimizing the hydropower allocation among power grids with a fixed energy control target over dry season or flood season is capable of improving the practicability and rationality of operation schemes;
- (3) The proposed method transfers amounts of hydropower from flood season to dry season, which can help to alleviate the increasing hydropower curtailment in Southwest China. Meanwhile, the power supply in dry season is effectively enhanced to provide more generation flexibility for coal-fired dominated power grids.

It should be mentioned that the application of the developed method to other similar hydropower systems should give full consideration to the differences in hydrology and storage capacity among rivers. These provide the basis for improving the operation policies of interprovincial hydropower plants. The power demands from recipient provinces are also important, because they greatly affect the choice of the optimization objective. It should also be noted that the present model was developed for monthly deterministic operations. Extensions of the model with stochastic inflows are recommended as a subject for further work. Besides, while solving short-term operations of interprovincial hydropower plants, this model also needs (as an improvement) to consider complex quarter-hourly load curves of multiple power grids and other necessary operation requirements.

Author Contributions: Conceptualization, J.-J.S. and J.Z.; Methodology, J.-J.S. and X.-F.Z.; Software, J.W.; Validation, R.C., and S.W.; J.-J.S. and X.-F.Z.; Investigation, J.Z.; Writing-Original Draft Preparation, J.-J.S.; Writing-Review & Editing, J.W., R.C. and S.W.

Funding: This research was supported by the open research fund of Key laboratory of dynamics and associated process regulations of the Pearl River Estuary, Ministry of Water Resources (No. [2018]KJ09), and the National Natural Science Foundation of China (No. 51579029).

Acknowledgments: The writers are very grateful to the anonymous reviewers and editors for their constructive comments. Specially, the writers want to express their thanks to the recommendation of the IEEEIC 2018—18th International Conference on Environment and Electrical Engineering.

Conflicts of Interest: The authors declare no conflict of interest.

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