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Optimization Model for the Short-Term Operation of Hydropower Plants Transmitting Power to Multiple Power Grids via HVDC Transmission Lines

CHENGGUO SU[1], CHUNTIAN CHENG[1], PEILIN WANG[2], AND JIANJIAN SHEN[1]
[1]Institute of Hydropower and Hydroinformatics, Dalian University of Technology, Dalian 116024, China
[2]School of Hydraulic Engineering, Yellow River Conservancy Technical Institute, Kaifeng 475004, China

Corresponding author: Chuntian Cheng (ctcheng@dlut.edu.cn)

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ABSTRACT Long-distance and large-capacity hydropower transmission from large hydropower plants in southwestern China to load centers is an important and effective measure for the accommodation of large-scale hydropower in China. However, the load demands of the receiving-end power grids are not fully considered in the conventional power transmission mode, which has greatly affected their enthusiasm for the absorption of trans-regional hydro energy. In order to make full use of the peak shaving capability of the hydropower plants, this paper develops an optimization model for determining the hourly generation scheduling of the hydropower plants transmitting electric power to several power grids via high voltage direct current (HVDC) transmission lines. A large-capacity and highly complex multi-unit hydropower system, the Xiluodu plant in China, is taken as the case study. In the proposed model, minimizing the peak-valley differences of multiple receiving-end power grids is adopted as the objective to alleviate the peak shaving pressure of the receiving-end power grids. In addition to the traditional hydraulic constraints, the operation constraints of individual units and HVDC power transmission limits are well considered. The study focuses mainly on modeling the stair-like power transmission curve constraint which is discrete and nonlinear and has been rarely considered in previous studies. This constraint is then linearized through limiting the logical relations between multiple binary integer variables. Case studies demonstrate that the proposed model has high computational efficiency, and the peak-valley differences of the two receiving-end power grids, i.e., Zhejiang Power Grid and Guangdong Power Grid, are decreased by 15.2% and 7.33%, respectively. Moreover, frequent conversion of HVDC converter equipment can also be avoided, which makes the obtained generation schedule more executable.

INDEX TERMS Hydropower plants, high voltage direct current, power transmission limits, peak shaving, Xiluodu plant.

NOMENCLATURE

A. SETS AND INDICES

G, g	Set and index of receiving-end power grids.
K, k	Set and index of equivalent generating units representing the power transmission curve of the HVDC transmission lines.
M, m	Set and index of the sections of the HVDC power transmission curve.
N, i	Set and index of hydropower units.
N_g	Set of the units transmitting electric power to the gth receiving-end power grid.
T, t	Set and index of time periods.

B. CONSTANTS

$C_{g,t}$	Original load demand of the gth receiving-end power grid in time period t[MW].
$\overline{C}_g$	Peak value of the original load demand of power grid g[MW].

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E_g	Daily transmitted hydro energy specified in the electricity contracts signed between the hydropower plant and power grid g [MWh].
I_t	Forecasted inflow of the reservoir in time period t[m^3/s].
$P_{i,\max}$	Maximum power output of hydropower unit i [MW].
$P_{g,k,\max}$	Maximum power output of equivalent unit k representing the power transmission curve of the gth HVDC transmission line [MW].
$P_{g,k,\min}$	Minimum power output of equivalent unit k representing the power transmission curve of the gth HVDC transmission line [MW].
$P_{g,k,fix}$	Fixed power output of equivalent unit k[MW].
$q_{i,\max}$	Maximum generating water flow of unit i[m^3/s].
w_g	Weighting coefficient of the gth objective function.
Y_i	Maximum shut-down times of unit i over the scheduling horizon.
$Y_{g,k}$	Maximum shut-down times of equivalent unit k over the scheduling horizon.
$Z_{\max}$	Upper bound of the forebay water level of the reservoir [m].
$Z_{\min}$	Lower bound of the forebay water level of the reservoir [m].
Z_{begin}	Initial forebay water level of the reservoir [m].
Z_{end}	Target forebay water level of the reservoir at the end of the scheduling horizon [m].
Δ_t	Duration of the tth time period [h].
δ	Allowable deviation between the terminal and target forebay water level of the reservoir.
ε	Allowable deviation between actual and specified delivered hydro energy.
α_i	Minimum required online duration of unit i[h].
β_i	Minimum required offline duration of unit i [h].
$\tau_{g,k}$	Minimum required online time of equivalent unit k[h].
$\gamma_{g,k}$	Minimum required offline time of equivalent unit k[h].

C. VARIABLES

$C'_{g,t}$	Residual load demand of the gth receiving-end power grid in time period t[MW].
$F_g^{'}$	Normalized peak-valley difference of the power grid g.
$H_{i,t}$	Net head of unit i in time period t [m].
$hl_{i,t}$	Penstock head loss of unit i in time period t [m].
$P_{g,t}$	Electric power delivered to power grid g in time period t [MW].
$P_{i,t}$	Power output of unit i in time period t [MW].
P_m	Transmission power of the mth-section power transmission curve [MW].
$P_{g,k,t}$	Power output of equivalent generating unit k representing the power transmission curve of the gth HVDC transmission line in time period t [MW].
Q_t	Total generating water flow of the hydropower plant in time period t [m^3/s].
$q_{i,t}$	Generating water flow of unit i in time period t [m^3/s].
S_t	Total spillage of the plant in time period t [m^3/s].
t_m	Dividing point of segment m-1 and segment m in power transmission curve.
$u_{i,t}$	Binary variable indicating if hydropower unit i is online in time period t.
V_t	Water storage of the reservoir at the end of time period t [m^3].
$v_{g,k,t}$	Binary variable indicating if equivalent unit k is online in time period t.
$x_{i,t}$	Binary variable indicating if hydropower unit i is started up in time period t.
$y_{i,t}$	Binary variable indicating if hydropower unit i is shut down in time period t.
$x_{g,k,t}$	Binary variable indicating if equivalent unit k is started up in time period t.
$y_{g,k,t}$	Binary variable indicating if equivalent unit k is shut down in time period t.
Z_t	Forebay water level of the reservoir at the end of time period t [m].
zd_t	Tailrace water level of the reservoir in time period t [m].

D. FUNCTIONS

$f_{zv}(\cdot)$	Forebay water level of the reservoir as a function of the water storage of the reservoir.
$f_{zq}(\cdot)$	Tailrace water level of the reservoir as a function of the total water discharge of the reservoir.
$f_{i,pqh}(\cdot)$	Power generation function of hydropower unit i with respect to the net head and generating water flow.

I. INTRODUCTION

Due to the increasing concern over the environmental impact of conventional fossil fuels, non-fossil energy has developed rapidly in China in recent years. Hydropower is a clean, renewable and cost-efficient source of energy. More importantly, hydropower can respond quickly to load changes and has huge untapped potential in China, and has therefore earned high development priority in China's energy plans [1]–[3]. According to statistics, by the end of 2018, the installed capacity of hydropower in China had reached 352 GW, accounting for approximately 20% of the nation's total installed electricity generation capacity [4]. Many huge hydropower plants have been put into operation in the past 20 years, such as the Three Gorges (22.4 GW), Jinping (8.6 GW), Xiangjiaba (6.4 GW), Xiluodu (12.6 GW), Xiaowan (4.2 GW), and Nuozhadu (5.85 GW). However, these large-capacity hydropower plants are mainly concentrated in the southwestern regions, far away from the load centers located in the eastern regions of China. Limited by the hydropower absorption capacity of local power grids, the produced hydro energy needs to be transmitted to faraway regions with high load demand to promote the utilization of renewable energy sources and reduce the hydropower curtailment in southwestern China [5]–[7]. Hence, China has decided to develop ultra-high and extra-high voltage direct current (UHVDC and EHVDC) power transmission technology, which features long distance, bulk capacity and high efficiency, to solve the dilemma of uneven distribution between energy sources and load centers [8]–[10].

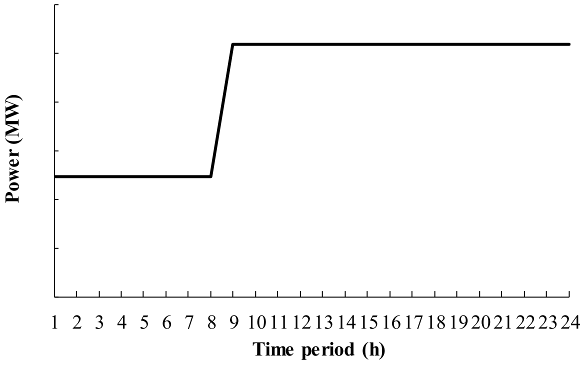


FIGURE 1. **The typical HVDC power transmission curve in conventional mode.**

So far, several HVDC projects for hydropower transmission have been built in China, such as the Xizhe Power Transmission Project, Xiangshang Power Transmission Project and Jinsu Power Transmission Project. These projects play an important role in the optimal allocation of hydro energy. However, the receiving-end power grids are generally coal-dominated energy systems, in which the peak-valley difference of the load demand is very large, and flexible power sources for peak shaving are not sufficient [11]. The shape of the hydropower transmission curve is usually a two-section line, and the power is fixed in each section, as shown in Fig. 1. This transmission mode is convenient for the unit commitment of the sending-end hydropower plants and can avoid the frequent conversion of HVDC converter equipment, but the load characteristics of the receiving-end power grids are not fully considered. What is worse, high amounts of received hydropower penetration increases the peak shaving pressure on the receiving-end power grids in many cases, which may present a great threat to the security and stability of these power grids. To reduce the operational risk, many receiving-end power grids do not want to receive the trans-regional hydro energy and require that the quantity of received electricity should not exceed 20% of their total energy consumption [12]. It is evident that the contradiction between sending-end hydropower plants and receiving-end power grids has greatly affected the enthusiasm of the latter towards the absorption of trans-regional hydro energy. Furthermore, as many large hydropower plants, including Wunonglong, Wudongde and Baihetan, will be soon put into operation in southwestern China, hydropower curtailment will become more and more serious in these regions if the power transmission mode does not change.

Considering that the hydro energy produced from hydropower plants is directly transmitted to the target region via HVDC transmission lines (known as point-to-point power transmission), this paper focuses on determining the short-term generation scheduling of sending-end hydropower plants, taking the receiving-end power grids' peak shaving demand into consideration. A large-capacity and highly complex multi-unit hydropower system - the Xiluodu plant in China - is taken as the case study. The Xiluodu plant is located downstream of Jinsha River and has an annual-regulation reservoir. It contains 18 generating units with a total installed capacity of 12600 MW. Among the 18 units, nine are installed in the left-bank hydropower plant, and the others are in the right-bank hydropower plant. According to the current operation plan, units in the left bank transmit electric power to Zhejiang Power Grid (ZJPG) via a ±800kV UHVDC tie-line, and the units in the right bank transmit electric power to Guangdong Power Grid (GDPG) via a ±500 kV EHVDC tie-line, as shown in Fig. 2. Compared to traditional high voltage alternating current (HVAC) power transmission, HVDC power transmission has tighter control requirements for avoiding the frequent conversion of HVDC converter equipment due to its very high cost. For example, the transmission curve should remain stair-like to maintain the smoothness of power transmission [10], [13], and the quantity of delivered hydro energy should meet the quantity specified in the contracts signed between the Xiluodu plant and the two receiving-end power grids. Overall, besides the hydraulic constraints, the operation constraints of individual units, power transmission limits and the load demands of the two receiving-end power grids should also be well considered. These complex constraints make the short-term operation of the Xiluodu plant very troublesome for system operators and researchers.

The above-mentioned problem is very different from the traditional operation of hydropower plants, which are required to satisfy the load demand of one single power grid [14]–[16] or aim to obtain greater power generation benefits [17]–[19]. Some relevant studies have been conducted in previous literatures. References [20] and [21] considered the short-term generation scheduling of the Xiluodu-Xiangjiaba cascaded plants and Three Gorges-Gezhouba cascaded plants, respectively, which transmit electric power to several power grids. References [22] and [23] formulated a linear programming (LP) and a nonlinear programming (NLP) optimization model, respectively, for the power allocation among multiple power grids. Reference [24] proposed a two-stage search method to determine the short-term generation scheduling of the cascaded hydropower

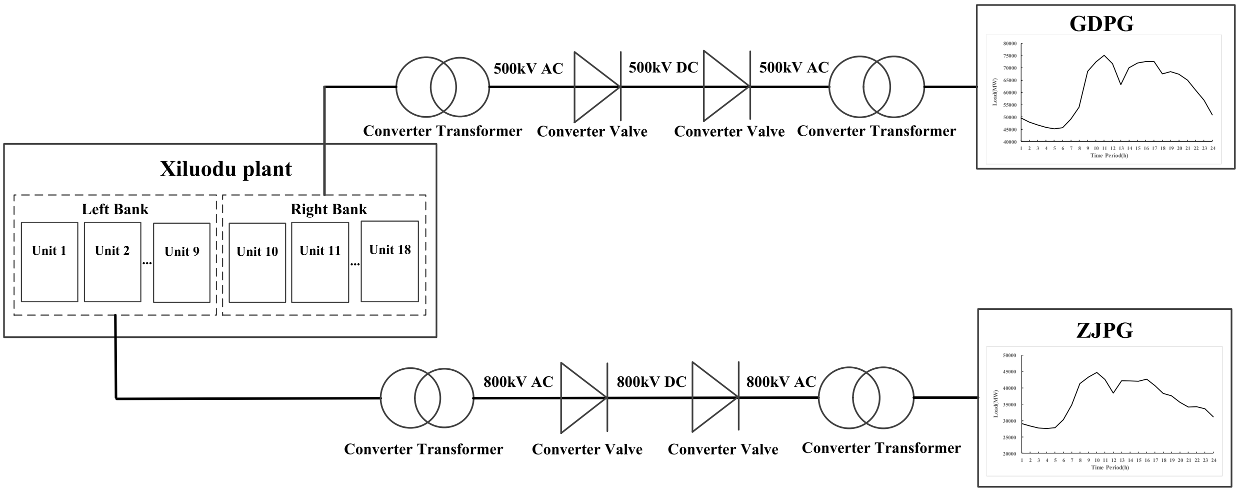


FIGURE 2. **Schematic diagram of the operation of the Xiluodu plant.**

plants transmitting electric power to multiple power grids through trans-provincial HVAC tie-lines. Reference [25] focused on determining the generation scheduling of a hydrothermal system which are required to satisfy the peak-shaving demands of multiple provincial power grids. Reference [26] proposed a plant-based generation scheduling model of four pumped-storage hydropower plants which are required to simultaneously provide peak shaving services for several provincial power grids, and then used a heuristic algorithm to solve this model. Reference [27] extended the work described in [26] from a plant-based model to a unit-based model to increase the accuracy, and then converted the original model into an MILP one using serval novel piecewise linearization techniques. However, few previous studies have involved the power transmission limits of HVDC transmission lines.

Short-term operation of the Xiluodu plant is essentially a short-term hydro generation scheduling (STHGS) problem. Various mathematical methods have been proposed to solve the STHGS problem in the past few years, including Lagrangian relaxation (LR) [28], dynamic programming (DP) [29], [30], artificial and computational intelligence approaches [31]–[39], and NLP approaches [40], etc. However, these methods present many difficulties in solving the problem described in this paper. With LR, it is generally difficult to find suitable Lagrange multipliers. DP suffers from the ‘‘curse of dimensionality’’ when faced with such a large-scale hydropower system, with 18 large-capacity units and very complicated operational constraints. The artificial and computational intelligence approaches such as genetic algorithm (GA) [31]–[33], differential evolution (DE) algorithm [34], [35], particle swarm optimization (PSO) [36]–[38] and bee colony optimization (BCO) [39], cannot guarantee a global optimum within finite iterations due to their random probability search mechanism, and it is hard to effectively handle the complicated spatial-temporal coupling constraints. The NLP formulation does not consider the start-up and shut-down statuses of individual hydropower units, thus it is not suitable for solving this problem. In recent years, mixed integer linear programming (MILP) has gained increasing popularity in solving STHGS due to the mature mathematical theory and the availability of more efficient commercial software [27], [41]–[44]. In this case, we can only focus on establishing the MILP formulation (i.e., converting the original MINLP formulation into an MILP formulation), and with the aid of efficient solvers, such as CPLEX and LINGO, the MILP approaches could generally obtain satisfied results within an acceptable CPU time [45].

Considering the above issues, this paper develops an optimization model for the short-term operation of the Xiluodu plant. This model aims to fully utilize the peak shaving capability of the sending-end hydropower plants and help alleviate the peak shaving pressure of the receiving-end power grids, thus, minimizing the peak-valley differences of multiple receiving-end power grids is adopted as the objective. In addition to the conventional hydraulic constraints, the operation constraints of individual units and the power transmission limits of the HVDC transmission lines are well considered. To covert the original mixed-integer nonlinear programming (MINLP) model into an MILP one, the nonlinearities in the model, including the objective function and the stair-like power transmission curve, are linearized using piecewise linearization techniques. Then, the formulated MILP-based model is solved by LINGO, an efficient commercial solver. In brief, the developed model has three key features:

1) The Xiluodu plant is divided into two independent plants which are called the left-bank plant and the right-bank plant, respectively. The nine units installed in the left bank transmit electric power to ZJPG, but the units in the right bank transmit electric power to GDPG, and the quantity of hydro energy delivered to each power grid should meet the requirements of the electricity contracts;

2) Although each unit has the same capacity (700 MW), the performance curves of all units are not the same since the units were produced by different manufacturing companies. Hence, each unit is considered individually. Moreover, the net head of the Xiluodu plant usually varies greatly during one day, hence the head effect on the performance of each unit is also taken into account to increase the accuracy of the model;

3) Power transmission limits are modeled to meet the control requirements of the HVDC converter equipment.

In comparison with previous works, the major contributions of this paper can be summarized as follows:

1) This is the first attempt to establish an MILP-based model for determining the short-term generation scheduling of hydropower plants which transmit electric power to multiple power grids via HVDC transmission lines.

2) In addition to the hydraulic constraints, the operation constraints of individual hydropower units, peak-shaving demand of the receiving-end power grids and the power transmission limits are also taken into account in this model to make the generation schedule more executable and to obtain the trans-regional coordination of the sending-end hydropower plant and receiving-end power systems.

3) Power transmission limits of the HVDC transmission lines are successfully modeled via a novel linear mathematical formulation in this paper, with considerations given to various operational constraints, including the stair-like power transmission curve constraint and the constraint on the quantity of hydro energy delivered daily.

The remainder of this paper is laid out as follows. Section II presents the mathematical formulation of the optimization model. Optimization results for the short-term operation of the Xiluodu plant are presented and discussed in Section III. Conclusions are finally provided in Section IV.

II. MATHEMATICAL FORMULATION

A. OBJECTIVE FUNCTION

As mentioned above, the objective of the optimization model is to alleviate the peak shaving pressure of the receiving-end power grids with the aid of Xiluodu's capability to quickly respond to load changes, whilst satisfying various physical constraints over the entire scheduling horizon. Minimizing the variance of the residual load series of the receiving-end power grids is usually taken as the objective function in conventional peak shaving models [23]–[26]. However, this function is nonlinear and difficult to transform into a linear formulation by using piecewise linear approximation techniques. Hence, minimizing the peak-valley difference of the residual load series of each receiving-end power grid is adopted as the objective function in this model, which is presented as

$$F_g = \min\left\{\max_{1\le t\le T}\left\{C'_{g,t}\right\} - \min_{1\le t\le T}\left\{C'_{g,t}\right\}\right\},\ g\in[1,G] \tag{1}$$

$$C'_{g,t} = C_{g,t} - P_{g,t} \tag{2}$$

$$P_{g,t} = \sum_{i\in N_g} P_{i,t} \tag{3}$$

However, (1) is a min-max form function, which is nonlinear and difficult to solve directly using commercial solvers. Thus, the objective function is converted into a linear function by introducing two auxiliary variables, $\overline{C'_g}$ and $\underline{C'_g}$.

$$F_g = \min\left\{\overline{C'_g} - \underline{C'_g}\right\},\quad g\in[1,G] \tag{4}$$

$$\begin{cases} C'_{g,t} \le \overline{C'_g} \\ C'_{g,t} \ge \underline{C'_g} \end{cases} \quad \forall t\in[1,T], \forall g\in[1,G] \tag{5}$$

It can be seen that the model is a multi-objective optimization problem as multiple power grids' peak-valley differences are expected to reduce. In general, multi-objective optimization problems are solved by reducing them to a scalar equivalent, and one effective measure is to aggregate several objective functions into a single one via the weighted method [46], [47]. Note that the load magnitude of these receiving-end power grids may vary greatly, meaning that the indicator, peak-valley difference, may not accurately reflect each power grid's demand for peak shaving. Hence, the load demand of each power grid should be normalized to avoid unreasonable optimization results. The final objective function for the optimization model is presented as follows.

$$\begin{cases} F = \min\left\{\sum_{g=1}^{G} w_g F_g^{'}\right\} \\ F_g^{'} = (\overline{C'_g} - \underline{C'_g})/\overline{C}_g \end{cases} \tag{6}$$

$F_g^{'}$ in Eq. (6) is also known as the ratio of peak-valley difference to peak load (RPDPL), and is an index often taken to measure the size of the peak shaving pressure on the power grid; w_g represents the importance of the peak shaving demand of power grid g. Here, it is preferred that $w_g = 1/G$ so as to ensure that the power grid with higher peak shaving pressure could be given greater consideration [22]–[24].

B. CONSTRAINTS

The operational requirements are modeled through the following constraints.

1) HYDRAULIC CONSTRAINTS

1) Water balance constraints

$$V_t = V_{t-1} + 3600(I_t - Q_t - S_t)\Delta_t \tag{7}$$

$$Q_t = \sum_{i=1}^{N} q_{i,t} \tag{8}$$

2) Water level limits

$$Z_{\min} \le Z_t \le Z_{\max} \tag{9}$$

$$\begin{cases} Z_0 = Z_{begin} \\ (1-\delta)Z_{end} \le Z_T \le (1+\delta)Z_{end} \end{cases} \tag{10}$$

2) INDIVIDUAL UNIT CONSTRAINTS

1) Power capacity limits

$$\begin{cases} 0 \le P_{i,t} \le u_{i,t} P_{i,\max} \\ u_{i,t} \in \{0, 1\} \end{cases} \tag{11}$$

2) Generating water flow limits

$$0 \le q_{i,t} \le u_{i,t} q_{i,\max} \tag{12}$$

3) Minimum online and offline duration constraints

$$\begin{cases} x_{i,t} + \sum_{\eta=t+1}^{t+\alpha_i-1} y_{i,\eta} \le 1 \\ y_{i,t} + \sum_{\eta=t+1}^{t+\beta_i-1} x_{i,\eta} \le 1 \\ x_{i,t}, y_{i,t} \in \{0, 1\} \end{cases} \tag{13}$$

$$\begin{cases} x_{i,t} - y_{i,t} = u_{i,t} - u_{i,t-1} \\ x_{i,t} + y_{i,t} \le 1 \end{cases} \tag{14}$$

4) Shut-down time limits

$$\sum_{t=1}^{T} y_{i,t} \le Y_i \tag{15}$$

5) Net head constraints of units

$$H_{i,t} = (Z_{t-1} + Z_t)/2 - zd_t - hl_{i,t} \tag{16}$$

$$Z_t = f_{zv}(V_t) \tag{17}$$

$$zd_t = f_{zq}(Q_t) \tag{18}$$

Generally, $hl_{i,t}$ is modeled as a quadratic function of the generating water flow. In this model, $hl_{i,t}$ is assumed to be a constant value during the whole scheduling horizon for the sake of simplicity. This assumption may introduce an error on the penstock head loss of each unit. However, this can greatly reduce the computational burden and the caused error is negligible compared with the net head. And one more thing to note that both (17) and (18) are nonlinear functions, meaning that (16) is also a nonlinear function.

6) Power production function

Since the Xiluodu plant has a large number of units whose types are not exactly the same and the operation status of each separate unit may vary at the same time, it is not appropriate to use just one power efficiency to represent the characteristics of all units. Moreover, although the Xiluodu plant is a hydropower system with a large storage capacity reservoir, the maximum possible net head variation could reach as much as 5 m in one day. Hence, it is inappropriate that the net head of the Xiluodu plant is regarded as a constant value during the course of one day. Overall, the power production function adopted in this model is expressed as (19), in which the net head effect on units' performance can be well considered.

$$P_{i,t} = f_{i,pqh}(q_{i,t}, H_{i,t}) \tag{19}$$

3) POWER TRANSMISSION LIMITS

1) Stair-like power transmission curve constraint

As mentioned earlier, the power transmission curve of HVDC tie-lines should remain stair-like to avoid the frequent conversion of HVDC converter equipment. This constraint can be expressed as follows.

$$P_{g,t} = \begin{cases} P_1 & t \in [1, t_1] \\ P_2 & t \in (t_1, t_2] \\ \vdots & \\ P_m & t \in (t_{m-1}, t_m] \\ \vdots & \\ P_M & t \in (t_M, T] \end{cases} \tag{20}$$

2) Daily transmitted energy constraints

The quantity of delivered hydro energy should meet the amount specified in the contracts signed between the sending-end plants and receiving-end power grids to ensure the benefit of the former.

$$(1-\varepsilon)E_g \le \sum_{t=1}^{T} P_{g,t} \le (1+\varepsilon)E_g \tag{21}$$

C. MILP-BASED MODEL FORMULATION

Three nonlinear constraints still exist in the formulated model (i.e., constraints (16), (19) and (20)), so the original MINLP formulation must be converted into an MILP one in order to apply the MILP approaches. The linearization methods for net head (constraint (16)) have been well established in [41], [42]. The hydropower production function (also known as the unit performance curves) described in (19) is a two-dimensional function, and the linearization of this function is usually implemented in two ways: 1) the unit performance curves are discretized into a series of nonlinear curves, and each curve relates to a specified net head interval. These curves are one-dimensional functions with respect to the power production and generating water flow, and then a piecewise linear formulation is used for the approximation of each curve [41]–[43]; 2) using meshing and triangulation techniques [44]. However, considering the accuracy and how easy it is to implement, the meshing and triangulation technique introduced in [44] has been taken to approximate the hydropower production function in this paper. Constraint (20) is discrete and nonlinear, and is rarely mentioned in the existing literatures. Therefore, this study has mainly focused on the linearization of the power transmission limits of the HVDC transmission lines.

1) LINEARIZATION OF POWER TRANSMISSION LIMITS

Given that the power transmission curve of HVDC transmission lines should remain stair-like, it is assumed that there are K equivalent generating units, and the power output of these equivalent generating units is superimposed to form the HVDC power transmission curve (as shown in Fig. 3). Then, modeling the HVDC power transmission constraints

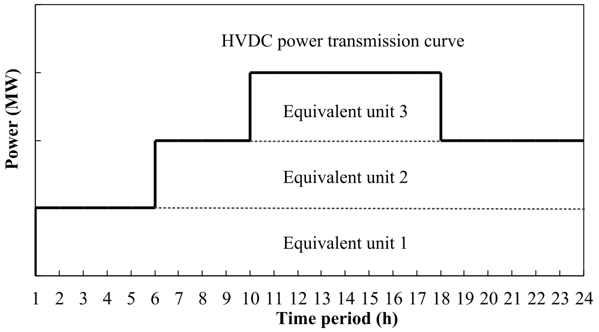


FIGURE 3. **Schematic diagram of modeling the HVDC power transmission constraints.**

can be considered as a unit commitment (UC) problem. For the equivalent generating units transmitting electric power to power grid g, the traditional UC constraints should be satisfied, which are expressed as follows.

1) Power output limits

$$v_{g,k,t} P_{g,k,\min} \le P_{g,k,t} \le v_{g,k,t} P_{g,k,\max} \tag{22}$$

In order to guarantee that the transmission curve remains stair-like, $P_{g,k,\min}$ is set equal to $P_{g,k,\max}$. Then, the power output limits of equivalent generating units can be expressed as (23), which denotes that the power output of equivalent unit k is limited to $P_{g,k,fix}$ as long as it is online.

$$P_{g,k,t} = v_{g,k,t} P_{g,k,fix} \tag{23}$$

The sum of the power output of all equivalent units in time period t is equal to $P_{g,t}$.

$$P_{g,t} = \sum_{k=1}^{K} P_{g,k,t} \tag{24}$$

2) Minimum online and offline duration constraints

$$\begin{cases} x_{g,k,t} + \sum\limits_{\eta=t+1}^{t+\tau_{g,k}-1} y_{g,k,\eta} \le 1 \\ y_{g,k,t} + \sum\limits_{\eta=t+1}^{t+\gamma_{g,k}-1} x_{g,k,\eta} \le 1 \\ x_{g,k,t}, y_{g,k,t} \in \{0, 1\} \end{cases} \tag{25}$$

$$\begin{cases} x_{g,k,t} - y_{g,k,t} = v_{g,k,t} - v_{g,k,t-1} \\ x_{g,k,t} + y_{g,k,t} \le 1 \end{cases} \tag{26}$$

3) Power adjustment times limits

The shut-down times of each equivalent unit is limited to avoid frequent adjustments of the transmission power.

$$\sum_{t=1}^{T} y_{g,k,t} \le Y_{g,k} \tag{27}$$

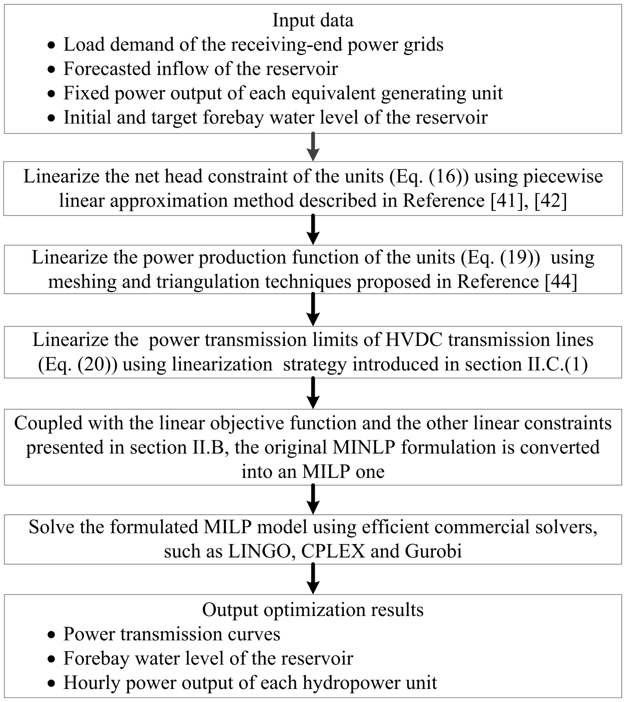
4) Power reversal limits

$$v_{g,k+1,t} \le v_{g,k,t} \tag{28}$$

Constraint (28) specifies the start-up order of the equivalent units. As shown in Fig. 3, the equivalent unit $k+1$ can only be started up when the equivalent unit k is online. Constraints (25), (26) and (28) ensure that no transmitting power adjustments can be made in the opposite direction within a short time period and ensure the control reliability of the HVDC transmission lines.

It is worth noting that, in practical application, parameters such as the number and capacity of equivalent generating units and the minimum online and offline time of equivalent units, etc., could be reasonably set according to the historical operation data of HVDC transmission lines, operators' experience, the power adjustment performance of HVDC converter equipment, and the upper and lower bounds of the injected electric power of receiving-end power grids.

Besides the above, hydropower plants generally operate at maximum power output during flood season to reduce hydropower curtailment, causing the transmission lines to have no margin for power adjustment. Thus, it is important to highlight that the developed model in this paper is more suitable for determining the generation scheduling during the non-flood season.


Input data
- Load demand of the receiving-end power grids
- Forecasted inflow of the reservoir
- Fixed power output of each equivalent generating unit
- Initial and target forebay water level of the reservoir

Linearize the net head constraint of the units (Eq. (16)) using piecewise linear approximation method described in Reference [41], [42]

Linearize the power production function of the units (Eq. (19)) using meshing and triangulation techniques proposed in Reference [44]

Linearize the power transmission limits of HVDC transmission lines (Eq. (20)) using linearization strategy introduced in section II.C.(1)

Coupled with the linear objective function and the other linear constraints presented in section II.B, the original MINLP formulation is converted into an MILP one

Solve the formulated MILP model using efficient commercial solvers, such as LINGO, CPLEX and Gurobi

Output optimization results
- Power transmission curves
- Forebay water level of the reservoir
- Hourly power output of each hydropower unit

FIGURE 4. **Flow chart describing the model solution based on the MILP approach.**

2) FLOW CHART OF THE MODEL SOLUTION BASED ON THE MILP APPROACH

The MILP-based model for the short-term generation scheduling of the Xiluodu plant can be constructed and solved with the above linearization techniques and strategies. A flow chart describing the model solution based on the MILP approach is given in Fig. 4.

TABLE 1. Characteristic parameters of the plants and reservoir.

$Z_{\max}$ (m)	$Z_{\min}$ (m)	Z_{begin} (m)	Z_{end} (m)
600	540	586.09	585.78

TABLE 2. Characteristic parameters of units.

Item	Left bank		Right bank
	#1-#6	#7-#9	#10-#18
Unit type	HE	VGS	DEC
$P_{i,\max}$ (MW)	700	700	700
$q_{i,\max}$ (m^3/s)	420	430	443
$hl_{i,t}$ (m)	1	1	1
α_i (h)	2	2	2
β_i (h)	2	2	2
Y_i	2	2	2

TABLE 3. Characteristic parameters of equivalent generating units representing power transmission curves.

Equivalent unit	To ZJPG			To GDPG		
	1	2	3	1	2	3
$P_{g,k,fix}$ (MW)	800	1200	1400	1000	1000	1200
$\tau_{g,k}$ (h)	3	3	3	3	3	3
$\gamma_{g,k}$ (h)	3	3	3	3	3	3
$Y_{g,k}$	2	2	2	2	2	2

III. CASE STUDY

The developed model was applied to the short-term optimal generation scheduling of the Xiluodu plant. The actual operation of the system for one day in April 2015 was used as a point of reference for this study. The characteristic parameters of the plant/reservoir and the units are shown in Table 1 and Table 2, respectively. The parameters of the equivalent generating units were set based on the analysis of a large number of historical operation data of the HVDC transmission lines, which are shown in Table 3. The forecasted inflow of the Xiluodu plant, and the load demands of ZJPG and GDPG are presented in Table 4. The historical quantities of hydro energy transmitted to ZJPG and GDPG were 55200 and 50900 MWh, respectively (i.e., $E_1 = 55200$ MWh, $E_2 = 50900$ MWh). Since no spillage is expected for the Xiluodu plant during non-flood season, S_t was set to 0 to accelerate convergence. The other parameters in the model were set as follows: $\delta = 0.1\%$, $\varepsilon = 3\%$.

The scheduling horizon was 24 hours, and each time period was set to 1 hour. The model was tested on a Dell workstation containing a 3.20-GHz Intel Core CPU with 4 cores and 8.0 GB of RAM, using LINGO, an efficient commercial solver.

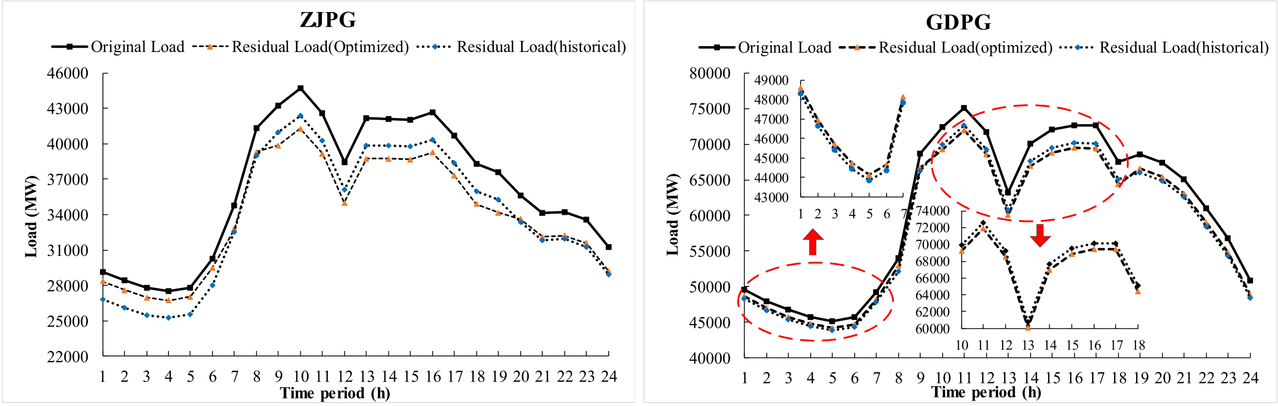
The optimized objective function value was 0.34784, and the CPU time was 419 s. The computational efficiency is believed to be acceptable, or even high, because of the considerations of individual unit constraints and HVDC power transmission limits in the developed model.

Optimization results and comparisons with the original load and the historical operation data are presented in Fig. 5 and Table 5. It can be clearly observed that, compared with original load, the peak-valley differences of both ZJPG and GDPG are reduced after optimization. This is because the proposed model has given full play to the peak shaving capability of the Xiluodu plant. At the same time, because the peak load of ZJPG is smaller but the received hydro energy of ZJPG is larger, the residual load curve of ZJPG is smoother than that of GDPG. As shown in Table 5, the peak-valley differences of the ZJPG and GDPG decreased by 15.2% from 17159 MW to 14559 MW and 7.33% from 29994 MW to 27794 MW, respectively. Besides, both the RPDPL and the standard deviation of the residual load curve for the two power grids are far smaller than those of the original load curve, demonstrating that the peak shaving pressure of the ZJPG and GDPG has been effectively relieved after optimization. Note that GDPG has a poorer performance in peak shaving in terms of the RPDPL of residual load series. This is mainly because the GDPG has a higher peak load value, which exceeds 75000 MW and is about 1.7 times larger than that of ZJPG. Moreover, compared with the residual load obtained from the historical operation data, the proposed model obtains a far smaller peak-valley difference for each power grid. Additionally, the RPDPL of ZJPG becomes larger after receiving the trans-regional hydro energy in conventional HVDC power transmission mode, although the peak-valley difference does not change. This is because the conventional HVDC power transmission mode does not consider the load characteristics of the receiving-end power grids and the transmission power is maintained at 2300MW during the course of one day. This situation is unreasonable and will increase the peak shaving pressure on ZJPG. Thus, it can be concluded that the optimization model could make better use of the Xiluodu plant's capability to quickly respond to load change and help alleviate the peak regulation pressure of multiple receiving-end power grids simultaneously.

Fig. 6 simultaneously shows the hourly power output of the left bank and right bank of the Xiluodu plant. It can be seen that the left bank and right bank operate at their respective minimum power output during off-peak hours (e.g., hours 1-6) and increase their power output during peak hours (e.g., hours 10-18), so as to respond to the load changes and smooth the load series of their corresponding receiving-end power grids. Moreover, since constraints

TABLE 4. Forecasted inflow of the Xiluodu plant and the load demands of ZJPG and GDPG.

Time period	1	2	3	4	5	6	7	8	9	10	11	12
Inflow (m^3/s)	1699	1699	2038	2038	1872	1872	2041	2041	1608	1608	2521	2521
Load demand of ZJPG (MW)	29140	28421	27777	27534	27825	30279	34799	41315	43260	44693	42579	38417
Load demand of GDPG (MW)	49606	47957	46702	45730	45141	45648	49161	53968	68681	72456	75135	71759
Time period	13	14	15	16	17	18	19	20	21	22	23	24
Inflow (m^3/s)	2015	2015	2018	2018	1850	1850	1696	1696	1865	1865	2036	2036
Load demand of ZJPG (MW)	42148	42132	42055	42668	40685	38309	37565	35642	34119	34225	33580	31224
Load demand of GDPG (MW)	63246	70122	72053	72653	72627	67560	68552	67392	65071	60972	56818	50860



(a) ZJPG

(b) GDPG

FIGURE 5. The residual load curves obtained from the proposed model and historical operation data.

TABLE 5. The statistical comparison between the optimization results and historical operation data.

Power grid	Item	Peak load (MW)	Valley load (MW)	Peak-valley difference (MW)	Ratio of peak-valley difference to peak load	Standard deviation (MW)
ZJPG	Original load	44693	27534	17159	38.4%	5788
	Residual load(optimized)	41293	26734	14559	35.2%	4802
	Residual load(historical)	42393	25234	17159	40.5%	5788
GDPG	Original load	75135	45141	29994	39.9%	10792
	Residual load(optimized)	71935	44141	27794	38.6%	9951
	Residual load(historical)	72635	43841	28794	39.6%	10313

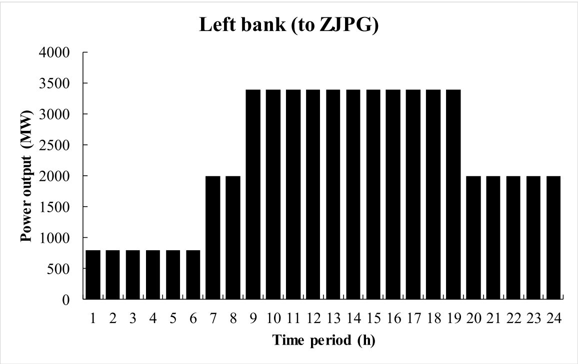
(22)-(28) are imposed, the power transmission curves remain stair-like, and no power adjustment is made in the opposite direction within a short time period. This implies that the proposed model could avoid the frequent conversion of the HVDC converter equipment, making the obtained generation schedule more executable. The daily transmitted hydro energy to ZJPG and GDPG are 56200 and 50800 MWh, respectively, which could meet the specified quantity of the transmitted hydro energy and ensure the generation benefit of the Xiluodu plant.

Fig. 7 plots the forebay water level of the reservoir. As shown, the forebay water level increases during hours 1-8 and decreases during hours 9-24, dropping by nearly 0.3 m throughout the whole scheduling horizon. The terminal forebay water level is 585.80 m, which is in an allowable deviation range with the target forebay water level.

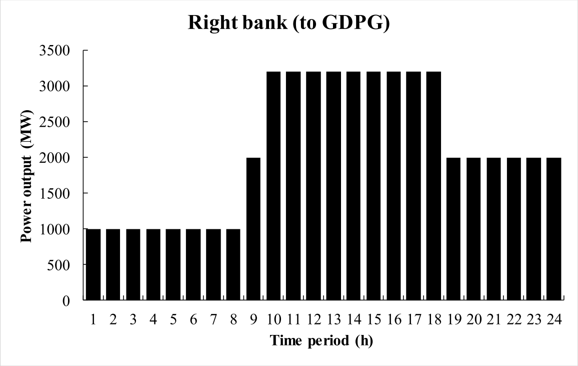
TABLE 6. Operation statuses of units in the Xiluodu plant.

Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
#1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
#2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#3	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
#4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
#5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
#6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1
#7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
#8	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
#9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#10	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
#11	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
#12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
#15	0	0	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1
#16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1
#17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#18	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Note: "1" denotes that the generating unit is online and "0" denotes that the unit is offline



(a) Left bank (to ZJPG)



(b) Right bank (to GDPG)

FIGURE 6. Hourly generation scheduling of the Xiluodu plant.

Fig. 8 shows the net head of unit #5 in each time period. As can be seen, the net head varies from 209.55 m to 214.24 m. Thus, the head effect on power generation of each unit cannot be neglected.

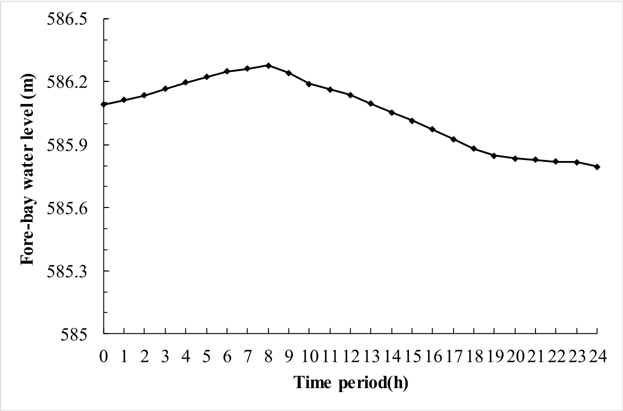


FIGURE 7. Forebay water level of the reservoir.

The operation statuses of each unit are presented in Table 6. As can be seen, all generating units can meet the requirements for the minimum online and offline time durations, and the shut-down times of each unit are no more than 2 throughout one day. That is to say, the optimization model could avoid the frequent startup and shutdown of each unit and ensure the stable operation of the Xiluodu plant.

The developed model and the commercial solver, LINGO, have been integrated into the decision support system (DSS) for the short-term operation of Xiluodu hydropower plant since 2018. When the system operators arrange the generation plan of the Xiluodu plant, they only need to input the load demand of each receiving-end power grid, the forecasted inflow of the reservoir and the fixed power

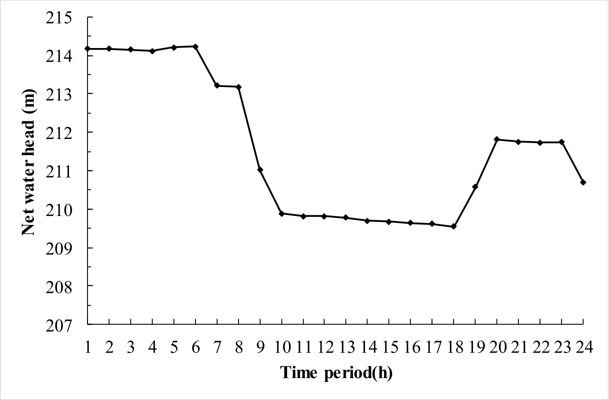


FIGURE 8. Net head of unit #5 in each period.

output of each equivalent generating unit into the DSS. The optimization results (e.g., power transmission curves, forebay water level of the reservoir, hourly power output of each hydropower unit) can then be obtained. Furthermore, the operators could change the default model parameters, such as $P_{i,\max}$ and $P_{i,\max}$, according to specific requirements for the operation of Xiluodu plant. This system greatly reduces the workload of the system operators and realizes the accurate and optimal scheduling of the Xiluodu plant.

IV. CONCLUSION

An optimization model for the short-term operation of hydropower plants transmitting electric power to multiple provincial power grids via HVDC transmission lines was developed in this paper. The Xiluodu plant, one of the most important power sources in the West-to-East Power Transmission Project in China and the most complex hydropower system in the world, was taken as an example. The model aims to fully utilize the peak shaving capability of the sending-end hydropower plants and help alleviate the peak shaving pressure of the receiving-end power grids. The performance of individual units and the head effect on the power generation were considered to increase the accuracy of the model. In particular, the formulation mainly deals with the constraints of HVDC power transmission, which has been rarely mentioned in other literatures. The stair-like power transmission curves are represented as the power outputs of a set of equivalent generating units. Through limiting the logical relations between online and offline variables of different equivalent generating units, the power transmission limits are modeled via a linear mathematical formulation. The efficient commercial solver, LINGO, was used to solve the formulated model and obtained satisfied optimization results in an acceptable computational time. The simulation results showed that the proposed model performed well at simultaneously flattening out load variations at the two receiving-end power grids, whilst meeting the specified quantity of the transmitted hydro energy and ensuring the stable operation of the Xiluodu plant. The power transmission curves of both the left bank and right bank remained stair-like, which could avoid the frequent conversion of the HVDC converter equipment and make the generation schedule more executable.

As increasingly large hydropower plants will be put into operation in southwestern China in the future, long-distance and large-capacity hydropower transmission to load centers via HVDC transmission lines will be an important measure for promoting hydroelectric utilization in China. Hence, the research on the short-term operation of the Xiluodu plant is believed to be of great significance and could provide an effective reference for the optimal operation of hydropower plants serving the West-to-East Power Transmission Project in China, such as Jinping plant, Xijiangba plant, Wudongde plant and Baihetan plant. It should be highlighted that the developed optimization model in this paper is a deterministic mathematical model without considering the uncertainty of the inflow of hydropower plants and the load demand of receiving-end power grids. In practical engineering, these two uncertainties will affect the scheduling results to some extent. Hence further research will be conducted on the effect of these two uncertainties to improve the robustness of the optimization model.

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CHENGGUO SU was born in Suzhou, Anhui, China, in 1994. He received the B.S. degree in hydraulic and hydropower engineering and the M.S. degree in hydraulic engineering from the Dalian University of Technology, Dalian, Liaoning, China, in 2014 and 2016, respectively, where he is currently pursuing the Ph.D. degree in electrical engineering.

His current research interests include the optimal scheduling of hydropower systems and optimal operation of multi-energy hybrid systems.

CHUNTIAN CHENG was born in Xiaogan, Hubei, China, in 1965. He received the Ph.D. degree in hydraulic engineering from the Dalian University of Technology, Dalian, China, in 1994.

Since 1999, he has been a Full Professor with the Dalian University of Technology. He has authored more than 200 articles and more than 50 inventions. His research interests include optimal operation of large-scale hydropower systems, scheduling of clean energy for interconnected power grids, and electricity market.

Dr. Cheng is currently the Changjiang Distinguished Professor and was a recipient of the National Science Fund for Distinguished Young Scholars, in 2010.

PEILIN WANG was born in Ruzhou, Henan, China, in 1991. She received the B.S. degree in engineering management from the North China University of Water Resources and Electric Power, Zhengzhou, Henan, China, in 2014, and the M.S. degree in hydrology and water resources from the Dalian University of Technology, Dalian, Liaoning, China, in 2017.

She is currently a Lecturer with the Yellow River Conservancy Technical Institute, Kaifeng, China. Her current research interests include optimal allocation and management of water resources.

JIANJIAN SHEN was born in Hongtong, Shanxi, China, in 1984. He received the B.S. degree in hydraulic and hydropower engineering from Shenyang Agricultural University, Shenyang, Liaoning, China, in 2006, and the Ph.D. degree in hydraulic and hydropower engineering from the Dalian University of Technology, Dalian, Liaoning, in 2011.

From 2012 to 2013, he held a postdoctoral position at the Control Science and Engineering Postdoctoral Research Station, Dalian University of Technology. He joined the Institute of Hydropower and Hydroinformatics, Dalian University of Technology, in 2014, where he has been an Associate Professor, since 2017. His current research interests include hydropower system operations, hydrothermal scheduling, and integrated management of renewable energy resources, electricity market, and decision support system development.

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