A Successive Approximation Approach for Short-Term Cascaded Hydro Scheduling with Variable Water Flow Delay

Xiaolin Ge [1*], Shu Xia [2], Wei-Jen Lee [3], and C. Y. Chung [4]

[1] Electric Power College, Shanghai University of Electric Power, Shanghai , China
[2] Shibei Electricity Supply Company of State Grid Shanghai Municipal Electric Power Company, Shanghai, China
[3] Energy Systems Research Center, University of Texas at Arlington, Arlington, USA
[4] The Department of Electrical and Computer Engineering, University of Saskatchewan, Saskatoon, SK S7N 5A9, Canada
[*] gexiaolin2005@126.com

Abstract: **In cascaded hydro systems, water delay time is a very important factor that requires coordination between upstream and downstream reservoirs. Due to the nonlinear characteristics of the water delay time, modeling and solving short-term cascaded hydro scheduling (STCHS) is a very challenging task. This paper proposes a novel STCHS model with continuous variation of water delay time to describe real-world operations in detail. The proposed model includes a nonlinear function related to water delay time. A successive approximation (SA) approach is developed to address the nonlinearity by iterative calculation, making the problem tractable. The proposed model and method are validated with two-reservoir and ten-reservoir systems. Numerical results demonstrate that the proposed method produces more realistic results than existing methods when dealing with STCHS problems.**

Keywords： **short-term scheduling; cascaded hydro systems; water delay time; successive approximation approach; real number**

Nomenclature

Indexes and sets

t	Index of time intervals (in h).
j	Index of hydro units.
k	Index of reservoirs or plants.
i	Index of upstream reservoirs or plants.
m	Index of piecewise water volume with power limits.

l	Index of piecewise water volume with Power Production Function.

Parameters

T	Time horizon of the problem (in 24 h).
J	Number of hydro units.
I	Number of upstream reservoirs or plants.
M	Number of segments in power limits.
L	Number of segments in power production function.
J_k	Set of hydro units of reservoir or plant k.
Δt	Length of each time interval (in h).
w_k^t	Natural inflow of reservoir k in time interval t (in m^3/s).
φ^t	Market price in time interval t (in \$/MWh).
$\underline{P}_{j,m}$, $\overline{P}_{j,m}$	Min and Max power outputs of unit j at water volume segment m (in MW).
V_k^{ini}	Initial water volume of reservoir k (in m^3).
V_k^{term}	Terminal water volume of reservoir k (in m^3).
$\underline{q}_j$, $\overline{q}_j$	Min and Max water flow values in unit j (in m^3/s).
$\underline{D}_k$, $\overline{D}_k$	Min and Max water release of reservoir k (in m^3/s).
$\underline{V}_k$, $\overline{V}_k$	Min and Max water volume of reservoir k (in m^3).
$\underline{p}_j^t$, $\overline{p}_j^t$	Min and Max power outputs of unit j in time interval t (in MW).
P_j^{cap}	Capacity of unit j (in MW).
$H_{j,m}$	Water volume for unit j at segment m in power limits (in m^3).
$\alpha_{j,l}$	Monomial coefficient of power production function for unit j in water volume segment l (in $MW/m^3/s$).

$\beta_{j,l}$	Constant term of power production function for unit *j* in water volume segment *l* (in MW).
$H_{j,l}$	Water volume for unit *j* at segment *l* in power production function (in m^3).
G_k	Set of all direct upstream reservoirs for reservoir *k*.
$D^t_{i,k,\mathrm{ini}}$	Water release from upstream reservoir *i* in time interval *t* of the previous day (in m^3/s).

Variables

f	Total profit (in $).
p^t_j	Power output of unit *j* in time interval *t* (in MW).
v^t_k	Water volume of reservoir *k* in time interval *t* (in m^3).
D^t_k	Water release of reservoir *k* in time interval *t* (in m^3/s).
u^t_k	Water release from all direct upstream reservoirs in past time that reaches reservoir *k* in time interval *t* (in m^3/s).
w^t_k	Natural inflow of reservoir *k* in time interval *t* (in m^3/s).
q^t_j	Water flow of unit *j* in time interval *t* (in m^3/s).
s^t_k	Spillage of reservoir *k* in time interval *t* (in m^3/s).
$q^t_{j,l}$	Water flow of unit *j* in time interval *t* at segment *l* (in m^3/s).
$u^t_{i,k}$	Water release from upstream reservoir *i* reaching reservoir *k* in time interval *t* (in m^3/s).
$u^t_{\mathrm{ini},i,k}$	Water release from previous scheduling time interval reached in time interval *t* (in m^3/s).
u^t_{i,k,t_1}	Water release of upstream reservoir *i* in time interval t_1 that reaches station *k* in time interval *t* (in m^3/s).
$\tau_{i,k,t}$	Water delay time from upstream reservoir *i* to reservoir *k* in time interval *t* (in h).
$D^t_{i,k}$	Water release from upstream reservoir *i* to reservoir *k* in time interval *t* (in m^3/s).
$K_{i,k,t_1,t}$	Coefficients of $D^{t_1}_{i,k}$ to the reaching water in time interval *t*.

$D_{\mathrm{av},i,k,t}$ Average water release from upstream reservoir *i* to reservoir *k* in time interval *t* (in m^3/s).

$\Phi(D_{av,i,k,t})$ Nonlinear water delay time function with respect to average water release.

1. Introduction

Short-term cascaded hydro scheduling (STCHS) aims to maximize the total profit or minimize the total operating cost of cascaded hydropower plants while satisfying various hydraulic and electrical constraints [1][2]. Typically, the time horizon is one day with hourly intervals [3]. This short-term scheduling is based on mid- to long-term cascaded hydro planning, and provides guidance for real time operations [4]. Effective STCHS results in significant potential energy savings and economic benefits, and many researchers have focused on this area in past decades.

Due to the cascaded hydraulic configuration, water release from upstream reservoirs will contribute to the inflow of downstream reservoirs after a certain time delay. Therefore, the water delay time is a crucial variable reflecting the relationship between upper and lower reservoirs. However, water delay time is often omitted in STCHS optimization models to simplify the calculation [5]. More recent studies include water delay time in the problem as a constraint, but it was assumed to be an integer constant [6][7]. A novel real number constant assumption for water delay time is proposed in [8]. Based on the stream flow routing curve presented in [9], water delay times ranging from the minimum to the maximum and the corresponding portion are considered in [10-12]. Furthermore, the well-known Muskingum method is used to describe the water travel process between two consecutive reservoirs in [13]. Notably, all of these models still assume that the value or the range of water delay time is given before the scheduling, neglecting any change of delay time with operating conditions [14]. Recently, [15] formulated water delay time as a variable, with consideration of the dynamic features. The lag time is discretized into integers to decrease the difficulty of the solution. However, a more accurate model for its description is still needed because the water delay time varies continuously.

In cascaded hydropower systems, reservoirs are connected in series or with a shunt connection, and water resource utilization is recycled. However, there is complex spatial-temporal coupling among stations. This makes STCHS very complicated, and generally modeled as a nonlinear, non-convex,

multi-constraint, and mixed integer programming problem [16]. Many methods have been developed to solve this problem, such as dynamic programming (DP) [17], Lagrange relaxation (LR) [18], mixed integer linear programming (MILP) [8], nonlinear programming (NP) [19], mixed integer nonlinear programming (MINLP) [20], and semidefinite relaxation (SR) [21]. Additionally, genetic algorithms (GA) [22], differential evolution (DE) [23], particle swarm optimization (PSO) [24], artificial bee colony (ABC) [25], and other modern heuristic algorithms have been successfully introduced to solve the STCHS problem. Extensive literature reviews are presented in [26-28]. As pointed out in [29] and [30], MILP has good performance with respect to adding constraints and solution efficiency, and has been widely applied to solve STCHS problems [8,15,29-32].

In consideration of a dynamic water delay time, optimization variables must change in spatial and temporal dimensions. The continuously varying water delay time is difficult to accurately convert to a MILP model and is very challenging for MILP to deal with. A successive approximation (SA) approach based on the iteration principle provides a new possible solution for this complex problem. In [32], SA is utilized to solve the generation scheduling problem with quadratic losses of power in transmission lines. In [33], the SA approach is used to obtain an equilibrium solution for joint optimization of two electricity producers, and is introduced in [34] to handle the hydro-thermal coordination problems to reduce the state numbers of the dynamic programming with significant improvements in solution efficiency. In [35], the SA method combined with neural networks is applied to estimate the dynamical nonlinear cost function of the grid. The advantage of the SA approach for the STCHS problem is that the nonlinear water delay time can be approximated by iteration; if the water delay time remains unchanged in each iteration, the problem can be easily transformed into a MILP formulation. So, the intention of this paper is to apply a successive approximation approach to solve the STCHS problem with consideration of continuous water delay time variables.

The main contributions of this paper are as follows:

1) A STCHS model is proposed that takes into account the continuous variation of water delay time. The mathematical representation of the hydraulic-electrical relationship is closer to actual operating conditions.

2) The range of water delay time variable is real number, which make the formulation of water routing time more refined.

3) SA along with MILP is adopted to solve this complex issue, with the continuous water delay time variables optimized by iterative procedures.

The paper is organized as follows. Section 2 states the STCHS mathematical formulation. The detailed water delay time model is described in Section 3. The application and improvement of SA is presented in Section 4. Section 5 provides numerical results from case studies. Conclusions are drawn in Section 6.

2. Mathematical model

2.1. Objective Function

This paper considers the cascaded hydro system operated under a deregulated profit-based environment. The objective of its operation scheduling problem is to maximize the total profit over the studied time horizon:

$$\max f = \sum_{t=1}^{T} \sum_{j=1}^{J} \varphi^t p_j^t \Delta t \,. \tag{1}$$

In the proposed model, day-ahead forecasts of stochastic quantities, for instance natural inflows or market price, are assumed to be accessible [36], and deterministic formulations are used in this paper.

2.2. Constraints

The above objective function is subject to the following constraints.

1) Hydraulic coupling among reservoirs

The water balance of the reservoirs in the cascade hydro system should be assured.

In this constraint,

$$v_k^t - v_k^{t-1} - 3600\Delta t(w_k^t - D_k^t + u_k^t) = 0 \,, \tag{2}$$

u_k^t is water release from all upstream reservoirs in past time t_1=t-τ that reaches station k in time interval t, τ is the water delay time (to be analyzed in the next section), and the constant “3600” represents 3600 seconds in one hour.

2) Reservoir level limits

This constraint,

$$\underline{V}_k \le v_k^t \le \overline{V}_k \,, \tag{3}$$

is related to water volume limits of reservoirs. Water volumes at the beginning and the end of the scheduling time are given by

$$v_k^0 = V_k^{ini} \quad \text{and} \tag{4}$$

$$v_k^T = V_k^{term} \,, \tag{5}$$

respectively, and are usually determined by mid-term scheduling [1].

3) Water flow limits

This constraint,

$$\underline{q}_j \le q_j^t \le \overline{q}_j \,, \tag{6}$$

reflects the lower and upper water flow bounds of hydro units.

4) Water release limits

The total amount of water released from the reservoir is defined by

$$D_k^t = \sum_{j \in k} q_j^t + s_k^t \,, \tag{7}$$

including water flow and spillage. The lower and upper water release bounds of the reservoir are

$$\underline{D}_k \le D_k^t \le \overline{D}_k \,, \tag{8}$$

5) Power output limits

According to

$$\underline{p}_j^t \le p_j^t \le \overline{p}_j^t \quad , \tag{9}$$

$$\underline{p}_j^t = \underline{P}_{j,m} \,, \quad H_{j,m-1} \le v_k^t \le H_{j,m} \;\; \forall j \in J_k \,, \tag{10}$$

$$\overline{p}_j^t = \min(P_j^{cap}, \overline{P}_{j,m}), \quad H_{j,m-1} \le v_k^t \le H_{j,m} \;\; \forall j \in J_k \,, \tag{11}$$

the upper and lower limits of power output are related to the operating level of the reservoir. Using the approach presented in [28], (9)-(10) can be converted to MILP formulations as follows:

$$\sum_{m=1}^{M} z_{j,m}^{t} H_{j,m-1} \le v_k^t \le \sum_{m=1}^{M} z_{j,m}^{t} H_{j,m} \qquad \forall j \in J_k \quad , \tag{12}$$

$$\sum_{m=1}^{M} z_{j,m}^{t} = 1 , \tag{13}$$

$$\underline{p}_j^t = \sum_{m=1}^{M} z_{j,m}^{t} \underline{P}_{j,m} , \tag{14}$$

$$\overline{p}_j^t \le P_j^{cap} , \tag{15}$$

$$\overline{p}_j^t \le \sum_{m=1}^{M} z_{j,m}^{t} \overline{P}_{j,m} , \tag{16}$$

where $z_{j,m}^{t}$ is auxiliary binary variable, if the reservoir *k* at period *t* works in volume segment m , the value is 1, otherwise 0. (12) and (13) determine the operating level of the reservoir, (14) represents min power outputs of unit *j* in time interval *t*, the max power outputs of unit *j* in time interval *t* is calculated by (15) and (16).

6) Power production function

In

$$p_j^t = \alpha_{j,l} q_j^t + \beta_{j,l} , \quad H_{j,l-1} \le v_k^t \le H_{j,l} \ \ \forall j \in J_k , \tag{17}$$

the power production is a function of water flow and water volume level in the reservoir. And this nonlinear function can be are transformed into a MILP function by

$$\sum_{l=1}^{L} \lambda_{j,l}^{t} H_{j,l-1} \le v_k^t \le \sum_{l=1}^{L} \lambda_{j,l}^{t} H_{j,l} \qquad \forall j \in J_k \quad , \tag{18}$$

$$\sum_{l=1}^{L} \lambda_{j,l}^{t} = 1, \tag{19}$$

$$\lambda_{j,l}^{t} \underline{q}_j \le q_{j,l}^{t} \le \lambda_{j,l}^{t} \overline{q}_j , \tag{20}$$

$$q_{j,l}^{t} \ge -\lambda_{j,l}^{t} (\beta_{j,l} / \alpha_{j,l}) , \tag{21}$$

$$p_j^t = \sum_{l=1}^{L} (\alpha_{j,l} q_{j,l}^{t} + \lambda_{j,l}^{t} \beta_{j,l}) , \tag{22}$$

$$q_j^t = \sum_{l=1}^{L} q_{j,l}^{t} , \tag{23}$$

where $\lambda_{j,l}^{t}$ is auxiliary binary variable for power production function, if v_k^t belongs to $[H_{j,l-1}, H_{j,l}]$, it equals to 1, otherwise 0; (18) and (19) descript the water volume level in power production constraint, (20) and (21) present the the upper and lower limits of water flow for unit *j* in time interval *t* at segment *l* ; and the generated power and water flow are expressed in (22) and (23).

It can be observed that except to nonlinear water delay time, the proposed model has been formulated as a MILP model.

3. Water delay time formulation

In the STCHS model, the effect of water delay time is mainly reflected in the hydraulic coupling equation. Because the scheduling horizon is one day, the water release u_k^t by all direct upstream reservoirs that reaches reservoir *k* can be expressed as

$$u_k^t = \sum_{i \in G_k} u_{i,k}^t = \sum_{i \in G_k} (u_{\mathrm{ini},i,k}^t + \sum_{t_1=1}^{T} u_{i,k,t_1}^t) . \tag{24}$$

Considering that the water delay time varies within a single day, the water delay time from upstream reservoir *i* to reservoir *k* in time interval t_1 (i.e., the interval $[t_1 - 1, t_1]$) is defined as τ_{i,k,t_1} . $D_{i,k}^{t_1}$ is the water release from upstream reservoir *i* in time interval t_1 that will reach the downstream reservoir in time interval $\left[t_1 - 1 + \tau_{i,k,t_1}, t_1 + \tau_{i,k,t_1}\right]$[8]. Taking into account that the time index is discrete while the water delay time is a continuous variable, as shown in Fig. 1, the delayed water releases from the upstream reservoir are divided into two sections: $\left[t_1 - 1 + \tau_{i,k,t_1}, \left\lfloor t_1 + \tau_{i,k,t_1} \right\rfloor\right]$ and $\left[\left\lfloor t_1 + \tau_{i,k,t_1} \right\rfloor, t_1 + \tau_{i,k,t_1}\right]$, where $\left\lfloor t_1 + \tau_{i,k,t_1} \right\rfloor$ means rounding down to the nearest integer.

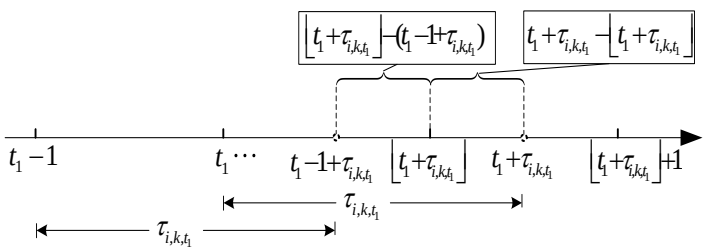


Fig. 1. The delay of water release

Thus, the water release of upstream reservoir i in time interval t_1 that reaches downstream reservoir k in time intervals $\lfloor t_1+\tau_{i,k,t_1} \rfloor$ and $\lfloor t_1+\tau_{i,k,t_1} \rfloor+1$ can be formulated as

$$\begin{aligned} u_{i,k,t_1}^{\lfloor t_1+\tau_{i,k,t_1} \rfloor} = u_{i,k,t_1}^{t_1+\lfloor \tau_{i,k,t_1} \rfloor} &= [\lfloor t_1+\tau_{i,k,t_1} \rfloor-(t_1-1+\tau_{i,k,t_1})]D_{i,k}^{t_1} \\ &= (\lfloor \tau_{i,k,t_1} \rfloor+1-\tau_{i,k,t_1})D_{i,k}^{t_1} \end{aligned} ; \tag{25}$$

$$\begin{aligned} u_{i,k,t_1}^{\lfloor t_1+\tau_{i,k,t_1} \rfloor+1} = u_{i,k,t_1}^{t_1+\lfloor \tau_{i,k,t_1} \rfloor+1} &= [(t_1+\tau_{i,k,t_1})-\lfloor t_1+\tau_{i,k,t_1} \rfloor]D_{i,k}^{t_1} \\ &= (\tau_{i,k,t_1}-\lfloor \tau_{i,k,t_1} \rfloor)D_{i,k}^{t_1} \end{aligned} . \tag{26}$$

It can then be concluded that

$$\begin{aligned} & u_{i,k,t_1}^{t} = K_{i,k,t_1,t}D_{i,k}^{t_1} \\ & K_{i,k,t_1,t} = \begin{cases} \lfloor \tau_{i,k,t_1} \rfloor+1-\tau_{i,k,t_1}, & \text{if } t=t_1+\lfloor \tau_{i,k,t_1} \rfloor \\ \tau_{i,k,t_1}-\lfloor \tau_{i,k,t_1} \rfloor, & \text{if } t=t_1+\lfloor \tau_{i,k,t_1} \rfloor+1 \\ 0, & \text{else} \end{cases} \end{aligned} \tag{27}$$

Thereafter, (24) can be converted into

$$u_k^t = \sum_{i\in G_k} u_{i,k}^t = \sum_{i\in G_k} (u_{\text{ini},i,k}^t + \sum_{t_1=1}^{T} K_{i,k,t_1,t}D_{i,k}^{t_1}) . \tag{28}$$

As demonstrated in (28), u_k^t may be related to the water releases for both the current and previous scheduling time intervals.

In previous studies, $\tau_{i,k,t}$ was set to be a constant, the value of which was determined from historical average values or operating experience. However, such a simplification will result in large deviations from the actual operation.

Without considering the flow flattening phenomenon, water delay time can be described as a function of the average velocity of the water flow $\mu_{i,k,t}$ and the distance between the upstream station section and downstream station section $\Delta x(i,k)$ [37]:

$$\tau_{i,k,t} = \frac{1}{3600}\frac{\Delta x(i,k)}{\mu_{i,k,t}} . \tag{29}$$

Because the average water release of upstream station $D_{\mathrm{av},i,k,t}$ is the product of average water flow velocity $\mu_{i,k,t}$ and the corresponding channel cross-sectional area $A_{i,k}$, meaning that $D_{\mathrm{av},i,k,t} = A_{i,k}\mu_{i,k,t}$, (29) can be rewritten as

$$\tau_{i,k,t} = \frac{1}{3600}\frac{A_{i,k}\Delta x(i,k)}{D_{\mathrm{av},i,k,t}} \quad , \tag{30}$$

$$D_{\mathrm{av},i,k,t} = \frac{1}{2}(D_{i,k}^{t-1} + D_{i,k}^{t}) \, . \tag{31}$$

Due to the fixed geographical distribution of the consecutive reservoirs, the channel cross-sectional area $A_{i,k}$ and the distance between the upstream and downstream station sections $\Delta x(i,k)$ are always constant and known. Thus, in (19), water delay time and average water release are related by an inversely proportional function.

In consideration of the flow flattening phenomenon, the relationship between water delay time and average water release becomes more complex. However, the principle that the water delay time will decrease as more water is released will still hold. As shown in Fig. 2, which is based on actual measured data from a reservoir in China, the water delay time can be fitted by a suitable nonlinear function when the fitting accuracy satisfies the requirement.

Finally, the proposed STCHS problem is modeled by (1)-(8), (12)-(16), (18)-(23)and

$$\tau_{i,k,t} = \Phi(D_{av,i,k,t}) \, . \tag{32}$$

Due to the variation of water delay time, the time indices in equations (25)-(27) (for example $t_1 + \lfloor \tau_{i,k,t_1} \rfloor$) are also varied, so the proposed problem cannot be solved directly by the MILP methods. Thus, SA along with MILP is proposed in this paper to solve this complex issue.

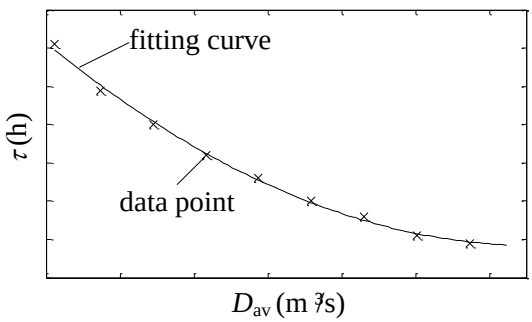


Fig. 2. Function of water delay time

4. Successive Approximation Approach

The SA approach [38] is adopted to deal with this problem because the nonlinear function related to water delay time is taken into account in the proposed model.

For convenience of description, the STCHS model is expressed as:

$$\max \quad f(\mathbf{x}) \tag{33}$$

$$s.t. \quad \mathbf{e}(\mathbf{x},\mathbf{y}) \le \mathbf{h}, \tag{34}$$

$$\mathbf{y} = \mathbf{g}(\mathbf{x}), \tag{35}$$

where $\mathbf{y}$ is the vector of water delay time variables; $\mathbf{x}$ is the vector of the remaining variables such as power output, water flow, water release, etc.; (33) is the objective function (1); (34) represents MILP constraints; and constraint (35) is the equation of water delay time (32).

Due to the nonlinear characteristic of the water time delay function, the SA approach is developed to solve the problem iteratively. At the beginning of iterations (n=1), the initial value of $\mathbf{y}$ denoted as $\tilde{\mathbf{y}}$ is set by the water delay time in the previous day because the operating conditions for two adjacent days should be relatively close [3]. With the given $\tilde{\mathbf{y}}$, the complicated model can be converted to a tractable model:

$$\max \quad f(\mathbf{x}^{(n)}) \tag{36}$$

$$s.t. \quad \mathbf{e}(\mathbf{x}^{(n)},\tilde{\mathbf{y}}) \le \mathbf{h}. \tag{37}$$

Obviously, the above model (36)-(37) is similar to the traditional cascaded hydro optimal scheduling model with fixed water delay time parameters, and thus many effective algorithms can be utilized to solve it, for instance MILP [29]. Thereafter, according to (35), the calculated value of $\mathbf{y}$ for n-th iteration ($\mathbf{y}^{(n)}$) is obtained:

$$\mathbf{y}^{(n)} = \mathbf{g}(\mathbf{x}^{(n)}). \tag{38}$$

Furthermore, a convergence criterion is established that is the maximum error between the calculated and initial value of $\mathbf{y}$ vectors and is no more than $\varepsilon_{\max}$:

$$\max\left|\mathbf{y}^{(n)} - \tilde{\mathbf{y}}\right| \le \varepsilon_{\max} \tag{39}$$

where $\varepsilon_{\max}$ is convergence precision. If (39) is not satisfied, indicating that the initial value of water delay time is unreasonable and should be regulated, we set $\tilde{\mathbf{y}} = \mathbf{y}^{(n)}$, let n=n+1, and execute iterative calculation again until the convergence demands are met.

Specific procedures of the proposed successive approximation approach are as follows:

1) According to the water release of the previous day, initialize the water delay time $\tilde{\tau}_{i,k,t}$. Define the number of iterations N, and set n=1.

2) Based on the given water delay time, formulate the STCHS problem.

3) Solve the model using MILP, and obtain the hydropower dispatching scheme and the optimized water release of all reservoirs.

4) Calculate the value of $\tau_{i,k,t}^{(n)}$ according to the nonlinear function of water delay time and average water release.

5) If the error $\max\left|\tau_{i,k,t}^{(n)} - \tilde{\tau}_{i,k,t}\right| \le \varepsilon_{\max}$, finish the iteration and output the result; otherwise, go to step 6.

6) Update $\tilde{\tau}_{i,k,t}$ with $\tau_{i,k,t}^{(n)}$. When all upstream plants have been analysed, set n=n+1 and go to step 2.

5. Case Studies

In this section, two case studies are used to investigate the effectiveness of the proposed model and method. The tests are carried out on a dual processor Intel Core i5 2450M with 2.50 GHz CPU, and 4 GB of RAM using a GAMS platform.

5.1. Two-reservoir Cascaded Hydro System

Detailed cascaded hydro system data are given in Table 1, where the first plant is the upstream plant, the second is the downstream plant, and the market price refers to [38]. In this paper, quadratic function is applied to fit the water delay time curve; as shown in Fig. 3, the fitting accuracy R-square value is 0.997.

Table 1
Parameters of two-reservoir cascaded hydro system

Reservoir No.	Capacity (MW)	$\bar{V}_k$ (10^4 m^3)	$\underline{V}_k$ (10^4 m^3)	$\bar{D}_k$ (m^3/s)	V_k^{ini} (10^4 m^3)	V_k^{term} (10^4 m^3)	Unit included
1	120	22485	5680	1249	16526.5	16195.9	1-3
2	139	4320	1865	2465	4276.8	4191.3	4-7

To compare different water delay time formulations, four operational scenarios are studied:

Scenario 1: the delay time is regarded as a constant and is determined based on the average water delay time of the upstream reservoir known from the previous day. MILP is applied to solve this model.

Scenario 2: the delay time is modeled as an integer variable and solved by MILP, in a similar manner as in [15], with its step function presented as the fine dotted line in Fig. 3.

Scenario 3: the delay time is modeled as an integer variable and solved by the combination of SA and MILP proposed in this paper.

Scenario 4: the delay time is modeled as a real number variable and solved by the combination of SA and MILP proposed in this paper. The corresponding curve is described by solid line shown in Fig. 3.

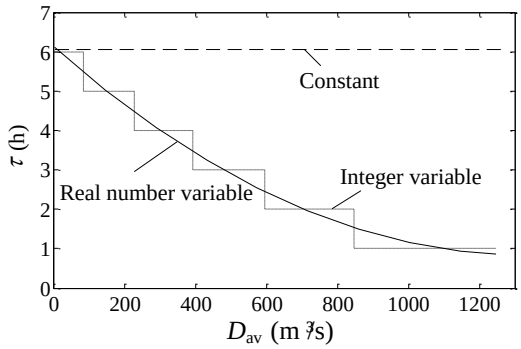


Fig. 3. Different water delay time curves

Table 2 shows that when the delay time is formulated as a variable (integer or real number), the CPU time is longer than the case in which the delay time is assumed to be a constant value. This is because iterative calculations or more constraints are required in the solution process of the delay time variable. However, the solution quality is significantly improved in Scenarios 2, 3, and 4 compared to Scenario 1. Moreover, the integer variable formulation and the proposed real number variable formulation increase the profit by 10.2% and 12.8%, respectively.

Table 2

Comparisons of the four scenarios

Scenario	Delay time formulation	Solution algorithm	# of discrete, continuous variables and constraints	CPU time (s)	Objective ($)
1	Constant	MILP[15]	4,080; 4,347;12,363	1.761	79245.853
2	Integer variable	MILP[15]	4,248; 4,707;13,299	6.015	87313.738
3	Integer variable	Proposed method	4,080; 4,347;12,363	6.137	87313.738
4	Real number variable	Proposed method	4,080; 4,347;12,363	6.258	89397.823

In Scenarios 2 and 3, the water delay time is assumed to be an integer variable and the optimization models are also the same, but the solution algorithms are different. In Scenario 3, the model is solved by the proposed method, and the convergence is reached after three iterations. In Scenario 2, the model is directly optimized by MILP, but more auxiliary variables and constraints are required to convert the model into the MILP formulation. Hence, as shown in Table 2, the computation time of Scenarios 2 is close to that of Scenarios 3. Tables 2 and 3 also show the optimized objective values and water delay times are the same in Scenarios 2 and 3. It has been discussed in [29] that MILP can provide a global or near-global optimal solution. The consistency of the solutions obtained in Scenarios 2 and 3 demonstrates that the proposed combination of SA and MILP can obtain a near-global optimal solution with reasonable convergence precision.

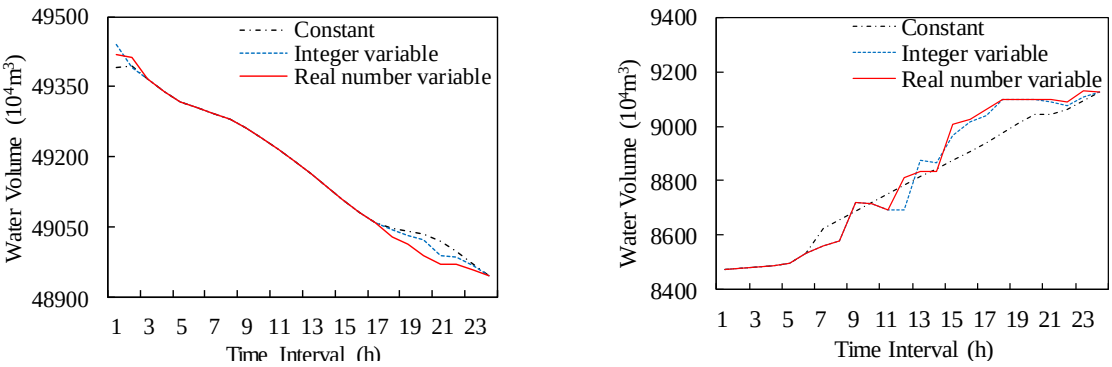
When water delay time is formulated as a real number variable in Scenario 4, the model cannot be directly solved by MILP as presented in [15]. However, it can be solved by the method proposed in this paper and the convergence is achieved at the third iteration. Additionally, as demonstrated in Table 3, the optimized hourly delay time resulted from the integer variable formulation deviates from the proposed formulation. This is because in the integer variable formulation, the step function is used to describe the delay time, while in the real number variable formulation, the nonlinear function is utilized. Obviously, the step function is less accurate than the nonlinear function.

Table 3

Comparisons of optimized delay time for scenarios 2, 3 and 4 (h)

Time interval No.	Scenario			Time interval No.	Scenario		
	2	3	4		2	3	4
1	5	5	5.48	13	5	5	5.34
2	5	5	5.48	14	5	5	5.48
3	6	6	6.11	15	5	5	5.48
4	6	6	6.11	16	5	5	5.48
5	6	6	5.48	17	5	5	5.48
6	5	5	5.48	18	6	6	5.48
7	5	5	5.48	19	6	6	5.48
8	5	5	4.74	20	6	6	6.11
9	5	5	4.74	21	5	5	6.11
10	5	5	5.34	22	5	5	6.11
11	5	5	5.34	23	5	5	6.11
12	5	5	5.34	24	5	5	6.11

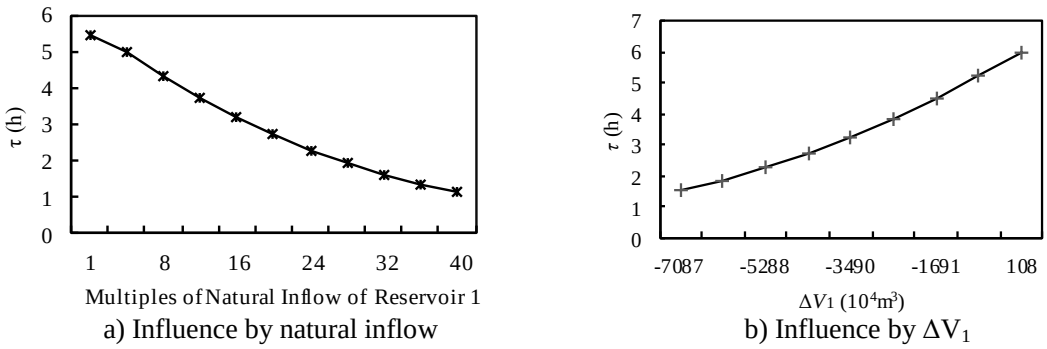
Fig. 4 summarizes the storage plans of the upstream and downstream reservoirs considering three different water delay time models. This figure shows that the optimized water storage schedules of the upstream reservoir are almost the same for all the three scenarios. However, the schemes of the downstream reservoir are very different. Compared with the plan for the scenario with real number variables, the plan for the scenario with integer variables has a certain bias for the hours 11 to 17. While the constant water delay time model causes very large deviations for hours 7 to 23, with a maximum deviation of 1.2204×106 m³. This occurs because the formulation of the water delay time has a large influence on the water balance of the downstream reservoir and, hence, affects the optimized water storage scheduling.



a) Upstream reservoir b) Downstream reservoir

Fig. 4. Storage plans of reservoirs

To investigate the variation of the optimized water delay time for the upstream reservoir, Fig. 5 analyzes two influencing factors: natural inflow and the difference between initial and terminal water volume ($\Delta V_1 = V_1^{term} - V_1^{ini}$). The curve in Fig. 5(a) illustrates that the water time delay decreases as the natural inflow of the upstream reservoir increases. This is because, with other calculation conditions unchanged, water release from the reservoir increases due to the increase in natural inflow. Accordingly, the delay time of water flow transferring from upstream to downstream is reduced. In Fig. 5(b), the water storage state of the upstream reservoir is varied by changing the difference between the initial and terminal water volumes; negative values mean that the reservoir must discharge water during this scheduling period, while positive values indicate that the reservoir needs to store water. With a decrease in water discharged and increase in water stored, less water is released and the water delay time increases.



a) Influence by natural inflow b) Influence by ΔV_1

Fig. 5. Variations of the optimized water delay time for the upstream reservoir

Fig. 6 presents the objective values caused by different storage states of the downstream reservoir. The storage state is expressed by ΔV_2 ($\Delta V_2 = V_2^{term} - V_2^{ini}$); the worst solution is related to the worst water delay time while the best solution is obtained from the optimal water delay time. When the value of ΔV_2 changes from positive to negative, the downstream reservoir changes from storing to discharging and the divergence between the best and worst solutions becomes smaller and even reaches zero. This demonstrates that the storage of the downstream reservoir during the study period is highly dependent on the water release from upstream plants; the arrival time of water flow from the upstream plant has a great impact on the scheduling of the downstream plant, and hence the divergence between the best and worst solutions is large. However, discharge from the downstream reservoir is not so sensitive to water release from upstream plants, and therefore the accuracy of water delay time has less effect on the objective solution.

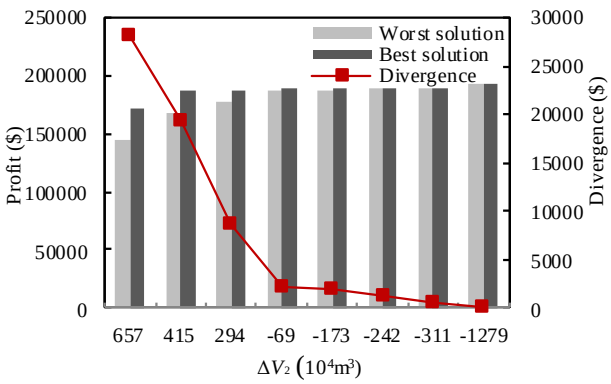


Fig. 6. Solutions of objective function based on storage state of downstream reservoir

5.2. Ten-reservoir Cascaded Hydro System

This test system is a real-world system in China including ten reservoirs with 34 hydro units. The schematic layout of this system is presented in Fig. 7 and the parameters of the reservoirs are listed in

Table 4. Water delay time curves of each upstream plant are shown in Fig. 8. Market price is the same as for the two reservoir test system.

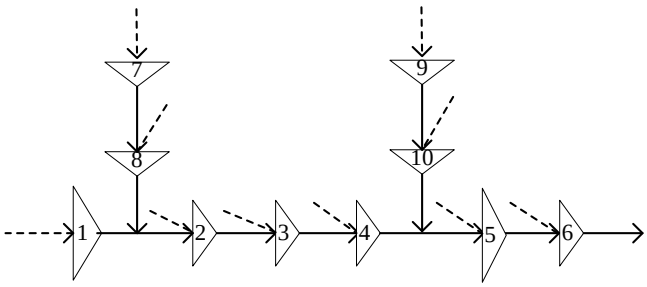


Fig. 7. Schematic layout of cascaded hydropower plants

Table 4

Parameters of the ten-reservoir cascaded hydro system

Reservoir No.	Capacity (MW)	$\bar{V}_k$ (10^4 m^3)	$\underline{V}_k$ (10^4 m^3)	$\bar{D}_k$ (m^3/s)	$V_k^{ini} = V_k^{term}$ (10^4 m^3)	Units included
1	120	89940	22720	1247	66106	1-3
2	139	17280	7460	2465	17107	4-7
3	120	3372	2024	3191	3372	8-10
4	250	42800	15600	4270	39590	11-15
5	600	111200	52400	5774	109310	16-20
6	210	24100	17760	6584	23136	21-24
7	17	6964	2007	1052	5759	25-27
8	72	9100	2660	1677	6479	28-30
9	100	5014	2304	1192	4914	31-32
10	30	1390	1014	1409	1370	33-34

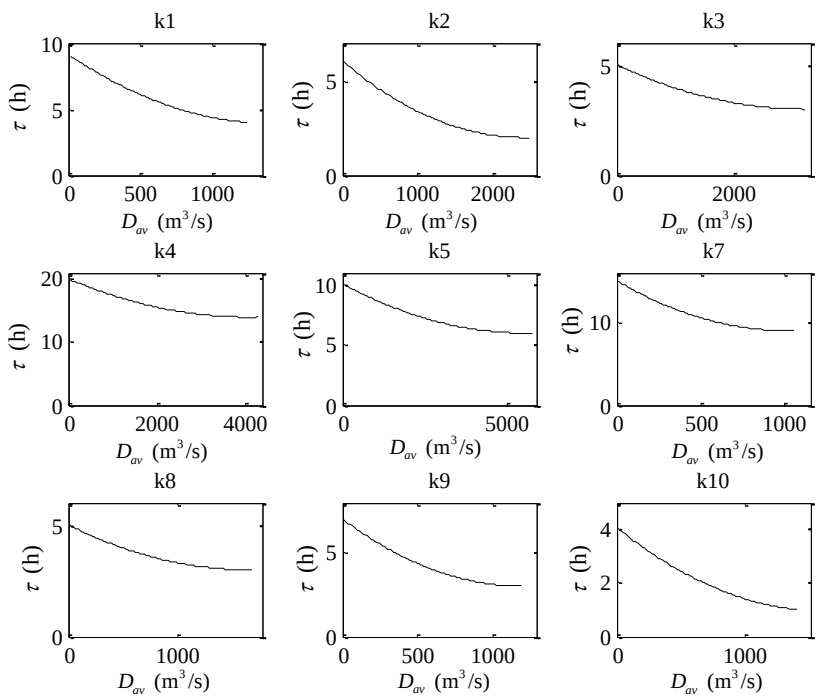


Fig. 8. Fitting curves of water delay time

In this case, it only takes 33.341 s to acquire the optimized hydro generation scheduling scheme. As illustrated in Fig. 9, the power outputs of the hydropower system can promptly follow price adjustments. When the price is higher, power output tends to increase as shown in time intervals 9-14 and 21-22.

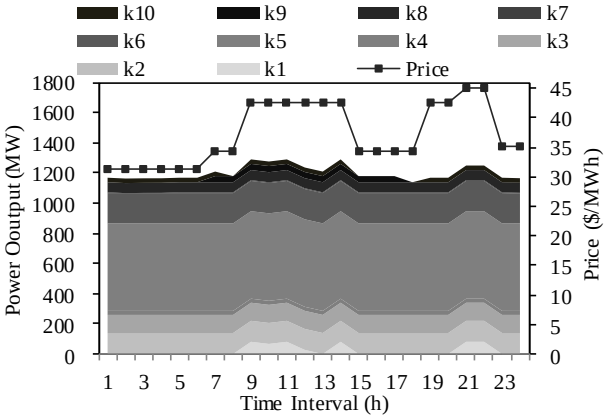


Fig. 9. Generation scheduling scheme of hydropower plants

To verify the effectiveness of the proposed method when considering the hourly water delay time formulation and the ten-reservoir cascaded hydro system, Scenarios 1, 2, and 4 presented in Section 5.1 are used. The convergence precision of Scenario 4 is set to 0.01.

As shown in Table 5, Scenario 4 can yield a high-quality solution with a small time increase compared to Scenarios 1 and 2, due to the more refined formulation of the delay time. With the hourly water delay time variable, in Scenario 4, the convergence is successfully achieved after eight iterations. The optimized delay times are provided in Table 6, and the evolution trends of the profit and error across the iterations are presented in Fig. 10. The intermediate solution obtained in the iterative process (iteration 3) is better than the profit obtained after reaching the convergence. However, this intermediate solution should be discarded because its error is bigger than the convergence precision, which means that this solution does not satisfy the nonlinear function of the water delay time and, hence, is infeasible. The optimized solution is feasible only when the convergence is reached.

Table 5

Comparisons of different formulations in a ten-reservoir hydro system

Scenario	# of discrete variables	# of continuous variables	# of constraints	CPU time (s)	Objective ($)
1	23,496	20,277	57,477	4.232	1,069,131.25
2	25,176	23,877	66,837	26.013	1,072,632.99
4	23,496	20,277	57,477	33.341	1,083,541.37

Table 6

Optimized hourly water delay time (h)

Upper and lower reservoir No.	Time interval											
	1	2	3	4	5	6	7	8	9	10	11	12
1-2	9.136	9.136	9.136	9.136	9.136	9.136	9.136	9.136	8.911	8.475	8.475	8.475
2-3	5.271	5.673	4.533	5.432	4.248	5.673	4.431	5.673	5.673	4.856	5.673	5.673
3-4	3.537	4.773	4.773	4.773	4.45	4.773	4.701	4.773	4.529	4.473	4.613	4.738
4-5	14.534	19.361	14.001	16.823	19.361	19.361	19.361	19.361	19.361	19.361	19.361	19.361
5-6	9.596	6.991	6.001	6.001	6.001	9.596	9.596	9.596	9.596	6.285	9.596	9.596
7-8	14.867	14.867	14.867	14.867	14.977	14.867	14.867	12.896	14.867	14.867	14.867	14.867
8-2	4.807	4.807	4.807	4.807	4.807	4.807	4.807	4.807	4.807	4.807	4.807	4.807
9-10	6.967	6.983	6.983	6.983	6.983	6.983	6.809	6.809	6.809	6.809	6.809	6.809
10-5	2.321	1.004	1.004	2.187	3.935	4.03	4.016	4.053	3.935	3.935	3.935	3.935
Upper and lower reservoir No.	Time interval											
	13	14	15	16	17	18	19	20	21	22	23	24
1-2	8.475	8.475	9.136	9.136	9.136	9.136	9.136	9.136	8.911	8.805	9.136	9.136
2-3	5.673	5.673	5.673	5.673	5.673	3.938	5.673	5.673	5.673	5.673	5.673	5.673
3-4	4.516	4.738	4.773	4.773	4.731	4.773	4.773	4.792	4.792	4.792	4.773	4.773
4-5	19.361	19.361	19.361	19.361	19.361	19.361	19.361	19.441	19.411	19.375	19.361	19.634
5-6	9.596	6.256	9.596	9.596	9.596	9.596	6.015	8.524	9.596	9.596	9.596	9.596
7-8	14.867	14.867	14.867	14.867	14.867	14.867	14.867	14.867	14.867	14.867	14.867	14.867
8-2	4.807	4.807	4.807	4.589	4.807	4.807	4.807	4.807	4.807	4.807	4.807	4.807
9-10	6.809	6.809	6.809	6.809	6.809	6.983	6.983	6.983	6.983	6.983	6.983	6.983
10-5	3.935	3.935	4.053	4.053	4.053	4.053	3.935	3.935	3.935	3.935	3.935	3.935

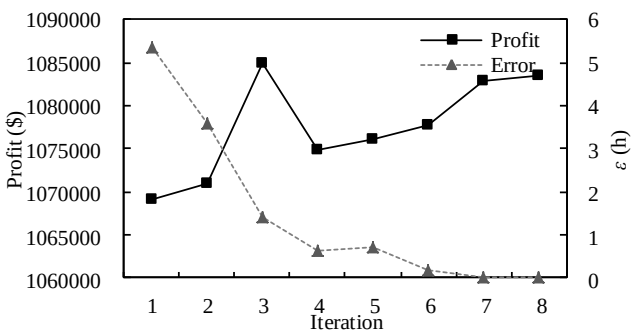


Fig. 10. Evolution trends of the profit and error

And to investigate the performance of this proposed method with great system, the scale of the testing system is expanded to 2, 4, 6, 8 and 10 times, respectively. As listed in Table 7, the greatest scale of the cases reaches 100 reservoirs with 340 units, including 437,541 variables and 574,671 constraints. By the proposed approach, the calculation can be converged successfully in all cases, and Fig.11 demonstrates that with the expansion of computing scale, the consuming time and profit almost linearly increase. It can be concluded that the proposed approach is still applicable to great cascaded hydro system.

Table 7

Calculation scale of testing system

Expanded times	# of reservoirs	# of units	# of variables	# of constraints
2	20	68	87,525	114,943
4	40	136	175,029	229,875
6	60	204	262,533	344,807
8	80	272	350,037	459,739
10	100	340	437,541	574,671

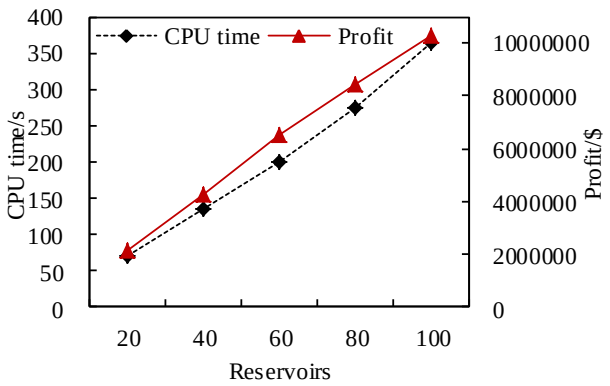


Fig. 11. The trend of computing time and optimized profit

6. Conclusions

This paper proposes a novel STCHS model that considers a real number water delay time variable. The successive approximation approach with MILP is employed to address this problem. Two sample systems are used to validate the proposed model and method. The main features are summarized as follows:

a) The real number variable formulation for water delay time has merit with respect to describing the continuous nonlinear variation of water flow transferring time. The proposed model can enhance the accuracy of the scheduling compared to existing constant and integer variable models.

b) The water delay time of the upstream plant depends on the storage state and natural inflow of the reservoir. Generally, if the upstream reservoir discharges more water, the natural inflow is increased and the water delay time tends to be smaller. In addition, more accurate water delay time estimation is needed when more water needs to be stored in the downstream reservoir.

c) In the great cascaded hydropower system, the proposed combination of SA and MILP can also keep its high computational efficiency to obtain a near-optimal solution with reasonable convergence

precision.

7. Acknowledgements

This work was supported in part by a National Natural Science Foundation of China grant (51507100), a “Chen Guang” project supported by the Shanghai Municipal Education Commission and Shanghai Education Development Foundation (14CG55), a Shanghai Sailing Program (No. 15YF1404600), and the “Electrical Engineering” Shanghai class II Plateau Discipline.

8. References

[1] J. I. Pérez-Díaz , J. R. Wilhelmi, and J. A. Sánchez-Fernández, Short-term operation scheduling of a hydropower plant in the day-ahead electricity market. Elect. Power Syst. Res., 80 (12) (2010) 1535-1542. Y. Zhao, X. Chen, Q. S. Jia, X. Guan, S Zhang, Y Jiang, Long-Term Scheduling for Cascaded Hydro Energy Systems With Annual Water Consumption and Release Constraints, IEEE Trans. on Automation Science and Engineering 7 (October) (2010) 969-976.

[2] R.-H. Liang and Y.-Y. Hsu, Short-term hydro-scheduling using Hopfield neural network. IEE Proc. Gener. Transm. Distrib., 143 (3) (1996) 269-275.

[3] L. Mo, P. Lu, C. Wang, and J. Zhou, Short-term hydro generation scheduling of Three Gorges–Gezhouba cascaded hydropower plants using hybrid MACS-ADE approach. Energy Convers. Manage., 76 (12) (2013) 260-273.

[4] P. Lu, J. Zhou, C. Wang, Q. Qiao, and L. Mo, Short-term hydro generation scheduling of Xiluodu and Xiangjiaba cascade hydropower stations using improved binary-real coded bee colony optimization algorithm. Energy Convers. Manage., 91 (2) (2015) 19-31

[5] Z. K. Shawwash, T. K. Siu, and S. O. D. Russell, The B.C. Hydro short term hydro scheduling optimization model. IEEE Trans. Power Syst., 15 (3) (2000) 1125-1131.

[6] L. V. L. Abreu, M. E. Khodayar, M. Shahidehpour , and L. Wu, Risk-constrained coordination of cascaded hydro units with variable wind power generation. IEEE Trans. Sust. Energy, 3 (3) (2012) 359-368.

[7] X. Li, T. Li , J. Wei, G. Wang and W. W. G. Yeh, Hydro unit commitment via mixed integer linear programming: a case study of the Three Gorges Project, China. IEEE Trans. Power Syst., 29 (3) (2014) 1232-1241

[8] B. Tong, Q. Zhai, and X. Guan, An MILP based formulation for short-term hydro generation scheduling with analysis of the linearization effects on solution feasibility. IEEE Trans. Power Syst., 28 (4) (2013) 3588-3599

[9] D. D. Ladurantaye, M. Gendreau, and J. Y. Potvin , Strategic bidding for price-taker hydroelectricity producers. IEEE Trans. Power Syst., 22 (4) (2007) 2187-2203

[10] T. M. Souza and A. L. Diniz, An accurate representation of water delay times for cascaded reservoirs in hydro scheduling problems. 2012 IEEE PES General Meeting, San Diego, CA, (Nov) (2012) 1-7.

[11] A. L. Diniz and T. M. Souza, Short-term hydrothermal dispatch with river-level and routing constraints. IEEE Trans. Power Syst., 29 (5) (2014) 2427-2435

[12] M. Chazarra, J. García-González, J. I. Pérez-Díaz, and M. Arteseros, Stochastic optimization model for the weekly scheduling of a hydropower system in day-ahead and secondary regulation reserve markets. Elect. Power Syst. Res., 130 (1) (2016) 67-77

[13] J. Wang and Y. Zhang, Short-term optimal operation of hydropower reservoirs with unit commitment and navigation. J. Water Resour. Plann. Manage., 138 (1) (2012) 3-12.

[14] F. Vassenden and G. Aronsen, Delay and loss of production water along the Orkla river. Energy Procedia, 87 (1) (2016) 149-156

[15] X.-l. Ge, L.-z. Zhang, J. Shu, and N.-f. Xu, Short-term hydropower optimal scheduling considering the optimization of water time delay. Elect. Power Syst. Res., 110 (5) (2014) 188-197

[16] M. Piekutowski, T. Litwinowicz, and R. J. Frowd, Optimal short-term scheduling for a large-scale cascaded hydro system. IEEE Trans. Power Syst., 9 (2) (1994) 805-811

[17] S. M. Amado and C. C. Ribeiro, Short-term generation scheduling of hydraulic multi-reservoir multi-area interconnected systems. IEEE Trans. Power Syst., 2 (3) (1987) 758–763

[18] E. Xi, X. Guan , and R. Li, Scheduling hydrothermal power systems with cascaded and head-dependent reservoirs. IEEE Trans. Power Syst., 14 (3) (1999) 1127-1132

[19] J. P. S. Catalao, S. J. P. S. Mariano, V. M. F. Mendes, and L. A. F. M. Ferreira , Scheduling of head-sensitive cascaded hydro systems: a nonlinear approach. IEEE Trans. Power Syst., 24 (1) (2009) 337-346.
[20] R. M. Lima, M. G. Marcovecchio, A. Q. Novais, and I. E. Grossmann, On the computational studies of deterministic global optimization of head dependent short-term hydro scheduling. IEEE Trans. Power Syst., 28 (4) (2013) 4336-4347.
[21] M. Paredes, L. S. A. Martins, and S. Soares, Using semidefinite relaxation to solve the day-ahead hydro unit commitment problem. IEEE Trans. Power Syst., 30 (5) (2015) 2695-2705.
[22] E. Gil, J. Bustos, and H. Rudnick , Short-term hydrothermal generation scheduling model using a genetic algorithm. IEEE Trans. Power Syst., 18 (4) (2003) 1256-1264.
[23] A. Glotić, P. Kitak, J. Pihler , and I. Tičar, Parallel self-adaptive differential evolution algorithm for solving short-term hydro scheduling problem. IEEE Trans. Power Syst., 29 (5) (2014) 2347-2358.
[24] J. Wu, J. Zhu, G. Chen, and H. Zhang, A hybrid method for optimal scheduling of short-term electric power generation of cascaded hydroelectric plants based on particle swarm optimization and chance-constrained programming. IEEE Trans. Power Syst., 23 (4) (2008) 1570-1579
[25] J. Zhou, X. Liao, S. Ouyang, R. Zhang, and Y. Zhang , Multi-objective artificial bee colony algorithm for short-term scheduling of hydrothermal system. Int. J. Elect. Power Energy Syst., 55 (2) (2014) 542-553.
[26] R.C. Bansal , Optimization methods for electric power system: a overview. Int. J. Emerging Electric Power Syst., 2 (1) (2005) 1-25.
[27] G. J. Osório , J. C. O. Matias , and J. P. S. Catalão , A review of short-term hydro scheduling tools. 48th Int. Univ. Power Eng. Conf. (UPEC), Dublin, (2013) 1-6.
[28] R. Taktak, C. D'Ambrosio, An overview on mathematical programming approaches for the deterministic unit commitment problem in hydro valleys. Energy Syst., 8 (2017) 57–79.
[29] G. W. Chang, M. Aganagic, J. G. Waight, J. Medina, et al., Experiences with mixed integer linear programming based approaches on short-term hydro scheduling. IEEE Trans. Power Syst., 16 (4) (2001) 743-749.
[30] E.C. Finardi, F.Y.K. ;Takigawa, B.H. Brito, Assessing solution quality and computational performance in the hydro unit commitment problem considering different mathematical programming approaches. Elect. Power Syst. Res., 136 (2016) 212–222
[31] A. Borghetti, C. D. Ambrosio, A. Lodi, and S. Martello, An MILP approach for short-term hydro scheduling and unit commitment with head-dependent reservoir. IEEE Trans. Power Syst., 23 (3) (2008) 1115-1124.
[32] C. Cheng, J. Wang, and X. Wu, Hydro unit commitment with a head-sensitive reservoir and multiple vibration zones using MILP. IEEE Trans. Power Syst., 31 (6) (2016) 1-11.
[33] T. N. Santos and A. L. Diniz , A dynamic piecewise linear model for DC transmission losses in optimal scheduling problems. IEEE Trans. Power Syst., 26 (2) (2011) 508-519.
[34] A. Haurie , R. Loulou, and G. Savard , A two-player game model of power cogeneration in New England. IEEE Trans. Autom. Control, 37 (9) (1992) 1451-1456.
[35] S. Ruzic , Vuckovic A., and N. Rajakovic , A flexible approach to short-term hydro-thermal coordination. II. Dual problem solution procedure. IEEE Trans. Power Syst., 11 (3) (1996) 1572-1578
[36] H. Nazaripouya and S. Mehraeen, Modeling and nonlinear optimal control of weak islanded grids using facts device in a game theoretic approach. IEEE Trans. Control Syst. Technol., 24 (1) (2016) 158-171.
[37] J. P. S. Catalão, H. M. I. Pousinho, and V. M. F. Mendes, Scheduling of head-dependent cascaded reservoirs considering discharge ramping constraints and start/stop of units. Int. J. Elect. Power Energy Syst., 32 (8) (2010) 904-910.
[38] H. J. Wagner and J. Mathur , Introduction to Hydro Energy Systems: Basics, Technology and Operation'(Berlin: Springer, 2011), 49-52.
[39] G. Y. Tang, H. Ma , and B. L. .Zhang, Successive-approximation approach of optimal control for bilinear discrete-time systems. IEE Proc. Control Theory Appl, 152 (6) (2005) 639-644.
[40] S. Bisanovic, M. Hajro, and M. Dlakic, Hydrothermal self-scheduling problem in a day-ahead electricity market. Elect. Power Syst. Res., 78 (9) (2008) 1579–1596.

Xiaolin Ge received the M.S. degree and Ph.D. in Electrical Engineering from North China Electric Power University, Beijing, China, in 2010 and 2013, respectively. In 2013, she joined the Shanghai University of Electric Power, where she is an associate professor. Her research interests include optimization of large-scale systems and scheduling of cascaded hydro power systems.(Email: gexiaolin2005@126.com)

Shu Xia received Ph.D. in Electrical Engineering from North China Electric Power University, Beijing, China, in 2014. Currently, he joined the State Grid Shibei Power Supply Company, where he is an engineer. His research interests include scheduling of power systems and mixed-integer nonlinear programming problems.

Wei-Jen Lee received the B.S. and M.S. degrees from National Taiwan University, Taipei, Taiwan, R.O.C., and the Ph.D. degree from the University of Texas, Arlington, in 1978, 1980, and 1985, respectively, all in Electrical Engineering. In 1985, he joined the University of Texas, Arlington, where he is currently a professor of the Electrical Engineering Department and the director of the Energy Systems Research Center. He has been involved in research on power flow, transient and dynamic stability, voltage stability, short circuits, relay coordination, power quality analysis, renewable energy, and deregulation for utility companies. Prof. Lee is a Fellow of IEEE and registered Professional Engineer in the State of Texas.

C. Y. Chung received the B.Eng. (with First Class Honors) and Ph.D. degrees in electrical engineering from The Hong Kong Polytechnic University, Hong Kong, China, in 1995 and 1999, respectively. He has worked for Powertech Labs, Inc., Surrey, BC, Canada; the University of Alberta, Edmonton, AB, Canada; and The Hong Kong Polytechnic University, China. He is currently a Professor, the NSERC/SaskPower (Senior) Industrial Research Chair in Smart Grid Technologies, and the SaskPower Chair in Power Systems Engineering in the Department of Electrical and Computer Engineering at the University of Saskatchewan, Saskatoon, SK, Canada. His research interests include smart grid technologies, renewable energy, power system stability/control, planning and operation, computational intelligence applications, and power markets. Dr. Chung is an Editor of IEEE Transactions on Sustainable Energy and an Associate Editor of IET Generation, Transmission, and Distribution. He is also an IEEE PES Distinguished Lecturer and a Member-at-Large (Global Outreach) of the IEEE PES Governing Board.