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A successive approximation approach for short-term cascaded hydro scheduling with variable water flow delay

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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.

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 Ref. [8]. Based on the stream flow routing curve presented in Ref. [9], water delay times ranging from the minimum to the maximum and the corresponding portion are considered in Refs [10–12]. Furthermore, the well-known Muskingum method is used to describe the water travel process between two consecutive reservoirs in Ref. [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, Ge et al. [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 Refs.

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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)
$\underline{P}_{j,m}$, $\bar{P}_{j,m}$	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)
$\underline{q}_j$, $\bar{q}_j$	Min and Max water flow values in unit j (in m^3/s)
$\underline{D}_k$, $\bar{D}_k$	Min and Max water release of reservoir k (in m^3/s)
$\underline{V}_k$, $\bar{V}_k$	Min and Max water volume of reservoir k (in m^3)
$\underline{p}_j^t$, $\bar{p}_j^t$	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
$D_{i,k,\mathrm{ini}}^t$	Water release from upstream reservoir i in time interval t of the previous day (in m^3/s)

Variables

f	Total profit (in $)
p_j^t	Power output of unit j in time interval t (in MW)
v_k^t	Water volume of reservoir k in time interval t (in m^3)
D_k^t	Water release of reservoir k in time interval t (in m^3/s)
u_k^t	Water release from all direct upstream reservoirs in past time that reaches reservoir k in time interval t (in m^3/s)
w_k^t	Natural inflow of reservoir k in time interval t (in m^3/s)
q_j^t	Water flow of unit j in time interval t (in m^3/s)
s_k^t	Spillage of reservoir k in time interval t (in m^3/s)
$q_{j,l}^t$	Water flow of unit j in time interval t at segment l (in m^3/s)
$u_{i,k}^t$	Water release from upstream reservoir i reaching reservoir k in time interval t (in m^3/s)
$u_{\mathrm{ini},i,k}^t$	Water release from previous scheduling time interval reached in time interval t (in m^3/s)
u_{i,k,t_1}^t	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)
$D_{i,k}^t$	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 $D_{i,k}^{t_1}$ to the reaching water in time interval t
$D_{av,i,k,t}$	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

[26–28]. As pointed out in Refs. [29,30], 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 Ref. [33], SA is utilized to solve the generation scheduling problem with quadratic losses of power in transmission lines. In Ref. [34], the SA approach is used to obtain an equilibrium solution for joint optimization of two electricity producers, and is introduced in Ref. [35] to handle the hydro-thermal coordination problems to reduce the state numbers of the dynamic programming with significant improvements in solution efficiency. In Ref. [36], 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.