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Short-term hydropower optimal scheduling considering the optimization of water time delay

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ABSTRACT

This paper is proposed to develop a novel mixed-integer model to solve the short-term hydropower optimal scheduling problem. The model is designed with consideration of the optimization of water time delay. The water time delay is the time required for discharging water from upstream reservoir to its downstream reservoir. It is always in change, which makes a real challenge to handle the corresponding mathematical models. In order to develop the model, we formulate water time delay as a nonlinear function of the outflow from upstream reservoir, which can describe the coupling of hydraulic and electric among cascaded hydropower stations accurately. Meanwhile, the complicated head-sensitive water-to-power conversion and piecewise output limits are also taken into account. To overcome the difficulty of solving the mixed-integer nonlinear optimization problem, the formulation above is converted into a mixed integer linear programming (MILP) problem in terms of integer algebra techniques. The applied commercial software is called CPLEX, which can solve the related MILP problem successfully. Based on a case study with 13 reservoirs and 44 hydropower units, the study shows that the proposed model with water-time-delay can improve the operability and economic benefits of scheduling.

1. Introduction

Hydropower resource is cascaded developed in large-scale, which can make full use of the whole basin water head. With the raising capacity for cascaded hydropower units, the refinement of hydro scheduling modeling has been brought into considerable benefit of power generation, promoting energy saving and emission reduction. For the significant economic and environmental impacts, hydropower optimal scheduling with cascaded stations has been an active research area over the past decades, and many studies on this topic have been reported. In [1], the model of long-term scheduling was presented with considerations of annually natural inflow uncertainty, electricity demand uncertainty, and government regulation on water resource allocation. In [2], the weekly scheduling problem of a large-scale hydrothermal power system was studied. The improved branch and bound algorithm were proposed to determine the hourly output power of cascaded hydro, thermal and pumped storage units during the entire week. The short-term hydropower-scheduling problem was presented in [3], and the power generations of generating hydro plants and water spillages during 24-h were scheduled.

In the research of the short-term hydro optimal scheduling, due to the cascaded hydraulic configuration, the outflow of an upstream plant will contribute to the inflow of the next downstream stations at a time later. At this point, both the electric relationship and hydraulic coupling should be considered in cascaded hydropower system [4]. As the existence of water time delay, the quantization of the dispatching objective function is related to the water of the day, as well as the day before that day. When there is a long distance between each cascaded hydropower station, compared with the time horizon of daily scheduling, the water time delay from upstream station to downstream station should not be neglected. However, Ref. [5] did not address the constraints relating to water time delay, which could not describe the water balance constraints and the hydraulic–electric coupling accurately. In [6–10], water time delay was formulated simply as a constant. While in fact, water time delay is always in change due to the variation of outflow from upstream reservoir. Besides, power system usually works closely with the feasible boundary in wet period, so the simple fixed water time delay model may result in a negative impact on both economy and security sides of the system. In [11], the dynamic character of flow travel time was described. However, it was still not considered in an integrated manner with an optimization model. The water time delay model considering streamflow routing was proposed in [12], which assumed that the maximum water delay times for different upstream outflows are the same, while the maximum water

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Nomenclature

Indexes

- t — index of time periods (in h), $t \in \{1, \ldots, T\}$. T is the scheduling time horizon (24 h)
- h — index of hydropower units, $h \in \{1, \ldots, H\}$. H is the total number of hydropower units
- i — index of hydropower unit sets
- h_p — index of reservoirs (or stations)
- k — index of upstream reservoirs (or stations)
- n — index of piecewise water outflow, $n \in \{1, \ldots, N\}$. N is the total number of water outflow segments
- r — index of piecewise water volume about water-to-power conversion constraints, $r \in \{1, \ldots, R\}$. R is the total number of water volume segments
- s — index of piecewise water volume about power limits, $s \in \{1, \ldots, S\}$. S is the total number of segments

Parameters

- Δt — length of each time period (in h)
- $R_{h_p,t}$ — natural inflow of reservoir h_p in period t (in m^3/s).
- U_p — set of direct upstream reservoirs of reservoir h_p.
- $\Delta t'$ — seconds included in period t (in s)
- $q_{\min,h}$, $q_{\max,h}$ — minimum and maximum water discharge of hydropower unit h (in m^3/s)
- $QS_{\min,h_p}$, $QS_{\max,h_p}$ — minimum and maximum outflow of reservoir h_p (in m^3/s)
- V_{ini,h_p}, V_{term,h_p} — initial and terminal reservoir storage volumes of reservoir h_p (in m^3)
- $V_{\min,h_p}$, $V_{\max,h_p}$ — minimum and maximum water storage volumes of reservoir h_p (in m^3/s)
- $P_{\max,i,t}$, $P_{\min,i,t}$ — upper and lower power limits of unit set i in period t (in MW)
- $Q'_{k,n}$ — outflow of hydropower station k at interval n (in m^3/s)
- $\tau_{k,n}$ — water time delay at interval n (in h)
- $QS_{\text{ini},k,t}$ — inflow from upstream station k in period t of the day before (in m^3/s)
- $V_{h,r}$ — storage volume of unit h in segment r about water-to-power conversion constraints (in m^3)
- $e_{h,r}$ — slope of water-to-power conversion function for hydropower unit h in volume segment r (in $MW/m^3/s$)
- $f_{h,r}$ — intercept of water-to-p ower conversion function for hydropower unit h in volume segment r (in MW)
- $\underline{P}_{h,s}$, $\bar{P}_{h,s}$ — upper and lower limits of hydropower unit h at volume interval s (in MW)
- $P_{h,\max}$ — capacity of hydropower unit h (in MW)
- $V_{h,s}$ — storage volume of unit h at interval s about power limits (in m^3)
- Ω_i — The ith hydropower unit set
- M — sufficiently large positive constant

Variables

- f — total generation (in MWh)
- $p_{h,t}$ — power output of unit h in period t (in MW)
- $v_{h_p,t}$ — water volume of reservoir h_p in period t (in m^3). For $t = 1$ it is assumed that $v_{h_p,t-1} = v_{h_p,0}$ (initial level).
- $s_{h_p,t}$ — spillage of reservoir h_p in period t (in m^3/s)
- $qs_{h_p,t}$ — outflow of reservoir h_p in period t (in m^3/s)
- $g_{k,t}$ — inflow into reservoir h_p in period t from the upstream hydropower station k (in m^3/s)
- $q_{h,t}$ — water discharge of unit h in period t (in m^3/s)
- $\tau_{k,t}$ — water time delay of hydropower station k in period t (in h)
- $\bar{p}_{h,t}$, $\underline{p}_{h,t}$ — upper and lower power limits of unit h in period t (in MW)
- $qr_{k,n,t}$ — auxiliary variable for water time delay constraints (in h)
- $q_{h,t,r}$ — water discharge of hydropower unit h in volume segment r at period t, which is divided into two sections (in m^3/s)
- $q'_{h,t,r}$ — one section of $q_{h,t,r}$ (in m^3/s), the value range of which is $[0, -f_{h,r}/e_{h,r}]$
- $q''_{h,t,r}$ — the other section of $q_{h,t,r}$ (in m^3/s), the value range of which is $[0, \max(0, q_{h,t,r} + f_{h,r}/e_{h,r})]$
- $\theta_{k,n,t}$ — binary variable used to decide whether the outflow $qs_{k,t}$ belongs to the interval n or not. If $qs_{k,t}$ is operated at interval $n(Q'_{k,n-1} \le qs_{k,t} \le Q'_{k,n})$, it equals 1, otherwise 0
- $d_{h,t,r}$ — binary variable of hydropower unit h in volume segment r at period t. If $V_{h,r-1} \le v_{h_p,t} \le V_{h,r}$, it equals 1, otherwise 0
- $d'_{h,t,r}$ — another binary variable of hydropower unit h in volume segment r in period t, noting that if the value of water discharge $q_{h,t}$ is greater than $-f_{h,r}/e_{h,r}$, $d'_{h,t,r}$ is 1, otherwise 0
- $z_{h,s,t}$ — binary variable of unit h at volume interval s in period t. If $V_{h,s-1} \le v_{h_p,t} \le V_{h,s}$, $z_{h,s,t}$ is 1, otherwise 0

delay times are different with different water release of upstream stations. Ref. [13] proposed a linear expression for water delay with decimal number, but the water time delays were still assumed as constants.

With the integrated consideration of the water time delay, the short-term hydro scheduling is a nonlinear, multiple constraints and mixed integer programming problem, which is a very challenging issue. Many methods have been developed to solve this problem, including dynamic programming (DP), Lagrangian relaxation approach, network flow, intelligent optimization algorithms, mixed integer linear programming method, etc. DP is the most widely used method for hydropower scheduling problem [14]. Nevertheless, it is difficult for DP to solve large-scale cascaded hydro scheduling problem due to the curse of dimensionality. In [15,16], Lagrangian relaxation was applied to solve coordinated scheduling of complex hydropower and hydrothermal system. Since the Lagrange multiplier of this method is difficult to adjust, as a result, the duality gap could not be effectively converged. In [17], network flow was used to solve the short-term hydrothermal scheduling problem, including hydraulic coupling constraints in cascaded hydro plants. However, the major limitation of this method is the inability to deal with discontinuous operating constraints. And the nonlinear programming (NLP) approach was presented to solve the daily hydro scheduling problem under electricity market in [18]. Intelligent algorithms methods, such as genetic algorithms [19], particle swarm optimization [20], and differential evolution [21,22] have been recently applied for solving the short-term hydro scheduling problem with good performance. Nevertheless, all the methods above generally depend on the expertise of the operator to properly calibrate the parameters. Mixed-integer linear programming (MILP) is a modern mathematical modeling technique. The advantage of this technique is that high accuracy solution can be obtained in a reasonable time [23]. In addition, with the development of the commercial software, MILP has been successfully