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Short-term generation scheduling model of Fujian hydro system

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ABSTRACT

The Fujian hydropower system (FHS) is one of the provincial hydropower systems with the most complicated hydraulic topology in China. This paper describes an optimization program that is required by Fujian Electric Power Company Ltd. (FEPCL) to aid the shift engineers in making decisions with the short-term hydropower scheduling such that the generation benefit can be maximal. The problem involves 27 reservoirs and is formulated as a nonlinear and discrete programming. It is a very challenging task to solve such a large-scale problem. In this paper, the Lagrangian multipliers are introduced to decompose the primal problem into a hydro subproblem and many individual plant-based subproblems, which are respectively solved by the improved simplex-like method (SLM) and the dynamic programming (DP). A numerical example is given and the derived solution is very close to the optimal one, with the distance in benefit less than 0.004%. All the data needed for the numerical example are presented in detail for further tests and studies from more experts and researchers.

1. Introduction

Fujian is one of the provinces on the southeast coast of China and rich in water power resources, with over 50% of the installed generating capacity (of about 10,500 MW) being hydroelectric at the end of 2000. Fujian Electric Power Company Ltd. (FEPCL)'s Dispatching and Communication Center (DCC) operates 27 reservoirs in five basins, with 27 hydroplants with a total of 83 units and an installed capacity of 3860 MW at the end of 2002.

The short-term hydropower scheduling problem of Fujian hydro system is simply expressed as follows: schedule the power generations of generating hydroplants and the water spillages from reservoirs such that the generation benefit during a planning period plus the water value stored at the end of planning period is maximal. With comprehensive elements involved, the short-term hydropower scheduling is typically a mixed, nonlinear and nonconvex optimization problem. Many optimization techniques have been applied to solve this problem, including dynamic programming, network flow method, linear programming, nonlinear programming, genetic algorithm, decomposition approach [3], progressive optimality algorithm, artificial neural networks [2], particle swarm optimization [5] etc. For more comments on these methods, the reader is referred to Labadie [1].

The Fujian hydropower system (FHS) is one of the provincial hydropower systems with the most complicated hydraulic topology in China. The schematic layout of the hydro system is shown in Fig. 1. This is a very challenging hydropower system and it's really not an easy task to solve such a large-scale short-term hydro scheduling problem in an acceptable execution time and with the required stability in giving satisfactory results.

The short-term hydropower scheduling problems of Fujian hydropower system (FHS) have been dealt with in our previous works by Wang et al. for energy production maximization [7] and energy consumption minimization [8]. With 27 reservoirs incorporated, a software was developed and has been used as a decision support tool to aid the users in making their decisions in day-to-day operations since 2000. The real-world problems were formulated as accurately as possible, with the generation and reservoir characteristics in tabular form and the objective functions with many flat localities. The local modification was employed to abate the water spillage and control the plant-based up/down frequency and time, which however made the method less adaptable to different hydro systems.

In this paper, the curves of generation and reservoir characteristics are represented analytically with quadric functions, rather than in tabular form. The analytical representation is used as it's more efficient to solve the problem in a mathematical way, despite the fact that this may cause greater deviation from the realistic situation. Actually, however, considering that the Fujian hydro system is so large in scale, this deviation is not so significant and is acceptable to the shift engineers who stand at a high level coordinating the generation schedules of 27 hydroplants. This paper also improves the previous models by incorporating more constraints, involving the outflow ramping constraints due to navigation requirements, the plant-based operating region, the systemwide spinning reserve, etc. Our previous works have used some heuristic

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Nomenclature

i, t respectively, indexes of reservoir/hydroplant and time interval
a_{i0}, a_{i1}, a_{i2} coefficients defining the relationship curve of water storage vs. forebay elevation of reservoir i
c_{i0}, c_{i1}, c_{i2} coefficients defining the relationship curve of outflow release vs. tailwater elevation of reservoir i
$D_t^{\max}, D_t^{\min}$ respectively, the maximum and minimum systemwide power in t (MW)
h_i^{ref} reference water head used to define the hydroplant generation characteristics (m)
h_{it} average water head of reservoir i in time interval t (m)
$h_{it}^{(k)}$ average water head of reservoir i in time interval t, which has been derived at the beginning of the k-th solving the hydro subproblem (m)
I_{it} local inflow to reservoir i in time interval t (m^3/s)
N the number of reservoirs/hydroplants
p_i generation output of hydroplant i, a function of the water head and the generation discharge (MW)
$p_i^{\max}$ maximum generation of hydroplant i, a function of the water head (MW)
p_{it} power generation of hydroplant i in time interval t (MW)
$q_i^{\min}, q_i^{\max}$ respectively, the limited minimum generation discharge and generation discharge capacity of hydroplant i, functions of the water head that are used to define the generation characteristics (m^3/s)
q_{it} generation discharge of hydroplant i in time interval t (m^3/s)
q_i^{u}, q_i^{l} respectively, the upper and lower bounds of the avoiding zone of hydroplant i, functions of the water head that are used to define the generation characteristics (m^3/s)
Q_{it} outflow from reservoir i in time interval t (m^3/s)
Q_i^{ini} average outflow from reservoir i in the time interval immediately before planning horizon (m^3/s)
$Q_{it}^{\max}, Q_{it}^{\min}$ respectively, maximum and minimum outflow from reservoir i in t (m^3/s)
r_{it} spinning reserve supplied by hydroplant i in time interval t (MW)
$R_t^{\min}$ minimum systemwide spinning reserve in t (MW)
spl_{it} water spillage from reservoir i in time interval t (m^3/s)
T planning horizon/period (h)
u_{it} operating state variable of hydroplant i in time interval t: 1 for 'up', and -1 'down'
v_i^{ini} water volume of reservoir i at the beginning of planning horizon (Mm^3)
v_{it} water volume of reservoir i at the beginning of t (Mm^3)
$v_{it}^{\max}$, $v_{it}^{\min}$ respectively, the maximum and minimum storages of i at the beginning of t (Mm^3)
v_{iT} storage of reservoir i at the end of planning horizon (Mm^3)
x_{it} up/down time of i at the beginning of t: positive for 'up', and negative 'down' (h)
x_i^{ini} initial status of up/down time of hydroplant i at the beginning of planning horizon (h)
x_i^{u}, x_i^{d} respectively, the minimum uptime and downtime of hydroplant i (h)
$y_i^{\max}$ maximum number of startups of hydroplant i
y_{it} decision on startup or shutdown for hydroplant i in t: 1 for 'startup', and 0 otherwise
z_{it} discrete variable representing the operating region of hydroplant i in t: 0 for 'down', 1 for the low feasible generation region, and 2 the high one above the avoiding zone
Z_i^{u}, Z_i^{d} respectively, the forebay and tailwater elevations of reservoir i (m)
$\delta_i^{\max}, \delta_i^{\min}$ respectively, the maximum and minimum outflow ramps of i [(m^3/s)/h]
γ_{i0}, γ_{i1}, γ_{i2} coefficients defining the generation output function of hydroplant i
λ_t the energy price in t (¥/MW h)
λ_{iT} water value rate of reservoir i at the end of planning horizon, a function of the water content at the end of planning horizon [¥/(h m^3/s)]
τ_i water traveling/delay time from i to it is immediate downstream reservoir (h)
$\Delta_i^{\min}$ decreasing rate of the limited minimum discharge of hydroplant i, which is used to define the generation characteristics [(m^3/s)/m]
$\Delta_i^{\max}$ decreasing rate of the generation discharge capacity of hydroplant i, which is used to define the generation characteristics [(m^3/s)/m]
Δt time length of one time interval (Ms)
Δv_{iT} dynamic storage of reservoir i at the end of planning horizon (Mm^3)
Ω_i set of the reservoirs immediate upstream to i

techniques based on experience that consequently makes it difficult for the previous approaches to adapt to more new constraints.

This paper introduces the Lagrangian multipliers to relax the constraints on the plant-based operating region and systemwide spinning reserve such that the primal optimization problem can be decomposed into two kinds of subproblems: a hydro subproblem and individual hydroplant subproblems. The former is a continuous and nonlinear optimization problem, which is progressively approximated as one with nonlinear objective function and linear constraints and is solved with the improved simplex-like method (SLM) by Wang [6]. The individual hydroplant subproblem only involves determining the optimal values of the discrete decision variables, the plant-based operating regions, and can be solved individually and independently by the dynamic programming (DP), which is more effective for such a case with a lower dimension and the objective function stage-separable. Two subproblems coordinate by updating the Lagrangian multipliers with a kind of subgradient method (SGM). The solution derived by solving the dual problem is usually not a feasible solution of the primal problem, which is achieved by an efficient heuristic policy that defines an incremental index to indicate the favorableness when the plant-based operating region is modified.

This paper is organized as follows. Section 2 formulates the short-term hydropower scheduling problem of Fujian hydro system. Section 3 shows how to decompose the primal problem into a hydro subproblem and many individual hydroplant subproblems using the Lagrangian multipliers, and how the individual hydroplant subproblem can be solved using the dynamic programming (DP). In Section 4, the solution procedure is described and the associated techniques are given. Section 5 gives and analyzes the numerical results with a typical 24-h scheduling problem of Fujian hydro system. Section 6 summarizes the paper.