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Parallel chance-constrained dynamic programming for cascade hydropower system operation

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ABSTRACT

With continuing development of hydropower in China, cascade hydropower system will account for more in the power grid, and may increase power grid operation risk under global climate change. This paper presents a parallel chance-constrained dynamic programming model to derive optimal operating policies for a cascade hydropower system in China. The innovation work of this paper is mainly embodied in two aspects. First, the reliabilities of meeting the firm power requirements of the cascade hydropower system and avoiding extreme system failure under extreme events are explicitly embedded in the model using Lagrangian duality theory and a penalty function. Multiple operating policies are generated by updating the values of Lagrangian multiplier and penalty coefficient for system disruption, then best operating rules are selected based on system performance and evaluated according to simulated reliability, extreme system failure, and maximum benefit. Second, the Fork/Join parallel framework is deployed to parallelize the chance-constrained dynamic programming in a multi-core environment for improving computational efficiency. Two computing platforms with contrasting configurations are employed to illustrate the parallelization performance. Results from a cascade hydropower system operation demonstrate that the proposed method is computationally efficient and can obtain satisfying operating policies, especially for extreme drought events.

1. Introduction

China has been experiencing an unprecedented hydropower boom since 2000 [1]. A large number of giant cascade hydropower stations have been built in southwest China in recent years, which are mainly characterized by large reservoir, huge installed capacity and long distance trans-regional power transmission [2], the cascade hydropower stations have become the main power source of the power system and account for a high proportion in the power generation mix [3]. Taking Yunnan province which located in southwest China as an example, the installed capacity of hydropower stations located on Lancang River and Jinsha River account for 22% and 28% of the installed capacity of Yunnan power grid respectively. As a power base for "West to East Power Transmission" (WEPT), the power transmission capacity from Yunnan to Guangdong and Guangxi is 21400 MW and 8150 MW respectively, which is about 20% and 23% of installed capacity of these two provinces. With continuing development of hydropower in the southwest China, cascade hydropower stations will account for more in the power grid, and have much greater impact on both sending and receiving power grid. Furthermore, the global climate change has increased the risk of extreme weather in recent years, how to cope with the affection of extreme drought to the cascade hydropower systems and keep the safety operation of the power grid will be an important challenge for southwest provinces of China.

Optimal operation rules of cascade hydropower system to

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Nomenclature

t	Index for time period
m	Index for reservoir
j	Index for iteration
c	Index for Lagrangian multiplier update
T	Number of time periods
M	Number of reservoirs in the system
$f_t^{opt}(\cdot)$	Optimal future value function at stage t
$B_t(\cdot)$	Benefits function for hydropower system at period t
$\mathbf{S}_t$	Storage vector of hydropower system at the beginning at period t
$\mathbf{S}_{t,\min}$, $\mathbf{S}_{t,\max}$	Lower and Upper bounds on storage at period t
$\mathbf{Q}_t$	Inflow vector during period t
$\mathbf{R}_t$	Release vector for period t
$\mathbf{R}_{t,\min}$, $\mathbf{R}_{t,\max}$	Lower and Upper bounds on reservoir releases at period t
$TR_t()$	Water balance equation at period t
$\mathbf{C}$	System connectivity matrix that maps the spatial flow connectivity of the reservoir network
$e_t(\mathbf{S}_t, \mathbf{S}_{t+1})$	Evaporation loss in period t
$\mathbf{q}_t$	Average turbine discharge vector during period t
$\mathbf{d}_t$	Average spilling discharge vector during period t
$\mathrm{P}(\mathbf{Q}_t)$	Probability of discrete inflow $\mathbf{Q}_t$ during period t
$p_{t,m}$	Power generation of reservoir m during period t
N_s	Firm power of the hydropower system
k_m	Generation efficiency of reservoir m
$q_{t,m}$	Average turbine discharge of reservoir m during period t
$H_{t,m}$	Net head of reservoir m at period t
$H_{t,m}^s$	Storage water level of reservoir m at period t
$H_{t,m}^w$	Tail water level of reservoir m at period t
$H_{t,m}^l$	Head loss of reservoir m at period t
$\bar{q}_m$	Upper bound of the average turbine discharge of reservoir m
γ	Hydropower system output guarantee rate
$\Pr(\cdot)$	The probability of satisfy hydropower system guaranteed output
δ	Constant for limiting the extreme system failure
μ	Penalty coefficient
λ^c	Lagrangian multiplier for update number c
φ^c	Updating coefficient for Lagrangian multiplier λ^c
γ^c	Simulated system reliability for update number c
μ^c	Penalty coefficient for update number c
η^c	Updating coefficient for penalty coefficient μ^c
$MINP^c$	Simulated extreme system failure for update number c
ε	Precision for iterative termination
PG^c	Average annual system benefit
L	Number of discrete values of $\mathbf{S}_t$
G	Number of discrete values of $\mathbf{Q}_t$
K	Number of discrete values of $\mathbf{R}_t$
$O(\cdot)$	Time complexity of the CCDP
J	Number of iterations
$T_E(M)$	Size of the computational tasks in an M-dimensional system
Lt	Logic threads
C_p	Number of processors
T_1	Execution time for the task undergoing serial processing
T_p	Execution time for the task using C_p cores

maximize the total generation benefit under complex energy demands and various operational constraints are very important for improving hydropower operation efficiency, which has attracted widely attention. Many studies have focused on hydropower operating rules. However, existing models mainly focus on determining the reliability of power generation [4], flood protection [5] or water supplies [6], but rarely consider extreme system failure in the worst case. In fact, especially for power generation models, severe failures [7] or severe energy generation shortages [8] are extremely destructive to the security of power system operations, as hydroelectric power is an important supplier for guaranteeing the stability of power systems. Therefore, extreme system failure should be considered in utility function, especially for hydro-dominated power grids.

The operation of cascade hydropower systems is strongly influenced by the stochastic nature of inflows [9]. It is widely recognized that operating policies for this problem should distinguish the risks associated with attaining different levels of system performance [10]. Chance-constrained reliability programming (CCP) is widely used in optimization and has the advantages of guaranteeing system performance and considering the risks of constraints violations [11]. It is well known that solving CCP problems is computationally challenging [12]. A number of optimization techniques have been developed for dealing with CCP problems, which may be divided in two parts: conventional optimization methods and heuristic algorithms. The conventional optimization methods available for CCP problems are improved based on some classical optimization methods, like chance-constrained linear programming (CCLP) [13], chance-constrained mixed-integer linear programming (CCMILP) [14], chance-constrained dynamic programming (CCDP) and methods based on improved dynamic programming [15]. CCLP was first introduced in constrained reliability [16]. However, it leads to overly conservative rules for reservoir operations [17], and both CCLP and CCMILP may not able to obtain the optimal result as the linearization of nonlinear constraints. With the rapid improvement of computer performance, heuristic algorithms like genetic algorithm (GA) [18], particle swarm optimization (PSO) [19], breeder hybrid algorithm (BHA) [20], simulated annealing (SA) [21] and bee colony optimization algorithm (BCO) [22] have been successfully used in solving hydropower system or energy system optimization problems. Incorporate with Monte Carlo simulation [23], heuristic algorithms are enable to solve CCP problems. Such as GA [24], PSO [25] and differential evolution [26] are widely used in solving CCP problems, but this require lots of simulation and is very time consuming. Furthermore, the solution of heuristic algorithms is unstable in different runs, which may not appropriate for real-world hydropower systems application [27].

CCDP was first presented by Askew and has become a commonly used approach for deriving operating policies and maximizing expected benefits, with systems being required to meet fixed levels of reliability [28]. Sniedovich and Davis commented on Askew's work and suggested introducing addition system variables to formulate chance-constraints [29]. Rossman introduced Lagrangian duality on the reliability constraints, which enabled convenient use of the dynamic programming procedure [30]. At present, CCDP has become an important method for solving uncertain problems like optimal control problem [31] or hydropower optimal operation [32]. Although CCDP is rigorous and conceptually flexible for deriving operating policies [33], the