



Peak operation of hydropower system with parallel technique and progressive optimality algorithm



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ABSTRACT

With the rapid economic growth in recent years, the peak operation of hydropower system (POHS) is becoming one of the most important optimization problems in power system. However, the rapid expansion of system scale, refined management and operational constraints has greatly increased the optimization difficulty of POHS. As a result, it is of great importance to develop effective methods that can ensure the computational efficiency of POHS. The progressive optimality algorithm (POA) is a commonly used technique for solving hydropower operation problem, but its execution time still grows sharply with the increasing number of hydropower plants, making it difficult to satisfy the efficiency requirement of POHS. To address this problem, a novel efficient method called parallel progressive optimality algorithm (PPOA) is presented in this paper. In PPOA, the complex problem is firstly divided into several two-stage optimization subproblems, and then the classical Fork/Join framework is used to realize parallel computation of subproblems, making a significant improvement on execution efficiency. The simulations in a real-world hydropower system demonstrate that as compared with the standard POA, PPOA can use abundant multi-core resources to reduce execution time while keeping the quality of solution, providing a new alternative to solve the complex hydropower peak operation problem.

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1. Introduction

Over the past few decades, China has been witnessing a high-speed economic growth period [1], which has greatly increased the demand for electricity [2]. For instance, in the East China Power Grid, from 2005 to 2011, the maximum load has increased from 87 GW to 176 GW, while the maximum peak-valley load difference has increased from 28.6 GW to 56.1 GW [3]. Thus, how to rapidly respond the load change during peak periods is becoming a huge challenge for operators in power system [4]. As one of the most important renewable energy resources, hydropower is often given high priority to shave the peak loads of power grids in China [5]. Hence, the peak operation of hydropower system (POHS) is chosen as the focus of this research.

Generally, the goal of POHS is to determine the optimal power generation of all the hydroplants over the scheduling horizon so as to obtain a smooth remaining load series left for low-efficiency generators [6–8]. Besides, POHS should satisfy a group of operational constraints imposed on both hydroplants and

hydropower system [9–11]. Mathematically, the POHS problem can be classified as a complex constrained optimization problem with the characteristics of multi-stage, nonlinearity and high-dimensionality [12,13]. To effectively solve this kind of problem, a wide range of optimization methods have been successfully developed by researchers all over the world [14–20], such as linear programming [21], nonlinear programming [22], dynamic programming (DP) and its variants [11], Lagrange relaxation and population-based evolutionary algorithms. Even though various degrees of success have been achieved in the practical engineering [18,23], there are still some defects in these classical methods. For instance, it is difficult for linear programming to address the existing nonlinearity of hydropower system [24,25]; in nonlinear programming, it may be NP-hard to solve indefinite quadratic problems because we have not proved theoretically whether there are polynomial algorithms for such problems [26,27]; in Lagrange relaxation, the choice of initial values and updating strategies of multiplier is not an easy work [28,29]; in evolutionary algorithms, the premature convergence cannot be avoided and the solutions obtained in the end are often instable [30–34].

Different from those aforementioned methods, DP can guarantee global optimal solution in the discrete state combinations

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and has no strict requirements on objective function and constraints, resulting in its widespread application to solve hydropower operation problems [35–37]. However, DP will suffer from the well-known “curse of dimensionality” as the problem scale expands [38–41]. Then, in order to alleviate the dimensionality problem, some DP variants represented by progressive optimality algorithm (POA) [42] and discrete differential dynamic programming [43] are proposed and have achieved a great deal of success in practical engineering. However, these modified DP methods can reduce the dimensions at different levels, but the computational cost still shows a rapid increase with the number of hydroplants [44], and may become intolerable once the problem scale reaches a certain large degree. This means that it is necessary to enhance the computational efficiency of methods for hydropower operation problem. Generally, there are two common ways to achieve this purpose: improvement of the algorithm mechanism or search some new and effective algorithms [45–47]. In this paper, we pay attention to the former group which is to alleviate the computing time of POA by using advanced computer technology.

In recent years, with the booming developing of computer technology, almost all the computers are installed processors with multiple cores, which has provides necessary hardware basis for the implementation of parallel computation [48,49]. Besides, many companies have successfully developed some simple but powerful parallel frameworks like Fork/Join and Message Passing Interface [50,51], providing the essential advanced software platform and condition for parallel computing. Generally speaking, in the multi-core environment, the complex father task is often recursively divided into several subtasks that will be solved on different cores at the same time, which can simultaneously reduce computational time and enhance algorithm performance. Thus, parallel computing has attracted a lot of attention from researchers and is becoming a hot research area in both computer science and electric power system [52]. However, to the best of our knowledge, up to now, there are still a few open reports about using parallel technology to resolve the time-consuming hydropower peak operation problem. Then, it is significant to use parallel technique to improve computational efficiency of hydropower peak operation problem.

Before the implementation of parallelization, the choice of parallel framework often has a great influence on the algorithm performance, and many factors must be taken into account [53], such as programming language, problem characteristic, application environment and operating system. In this research, the Fork/Join framework is given the first choice because it is the standard programs to realize parallel computing in Java Developer's Kit while our previous algorithms are encoded in Java language. Although Fork/Join may not have the best results in reducing execution time, it can provide satisfactory performance in most cases and guarantee the good cross-platform features of parallel algorithms. Next, after deeply analyzing the traditional POA that is executed in a serial way, we find that there are good parallel possibilities when solving two-stage optimization subproblems of POA. Then, by combining the advantages of Fork/Join and POA, a novel method named parallel progressive optimality algorithm (PPOA) is presented. The proposed PPOA is successfully applied to solve a cascade hydropower system operation in China. The results show that as compared with POA, the computing time of PPOA for the 10-plant and 3-state hydropower system is reduced by about 85% in 8-core environment, demonstrating the feasibility of parallel technology to reduce execution time of hydropower peak operation. To be summarized, the main contribution of this paper is given as below: parallel possibilities are found in POA's two-stage optimization subproblems, and the novel PPOA method is presented to enhance the execution efficiency of hydropower system peak operation problem.

The remaining of this paper is organized as below. Section 2 presents the mathematical model of the POHS problem. Section 3 gives the details of PPOA after introducing POA and Fork/Join framework. Section 4 gives the results of the proposed method in a real-world hydropower system of China. Finally, the conclusions are provided in Section 5.

2. Mathematical modeling

2.1. Variable definition

J	Number of periods.
K	Number of hydroplants.
C_j	Load demand of power grid at the j th stage.
V_k^{beg}	Initial storage of the k th hydroplant.
V_k^{end}	Terminal storage of the k th hydroplant.
$\tau_{l,k}$	Water transport period between hydroplant l and k .
Ω_k	Set of directly upstream hydroplant s above the k th plant.
$L_{k,j}^{\text{max}}$	Maximum power output of hydroplant k at the j th stage.
$L_{k,j}^{\text{min}}$	Minimum power output of hydroplant k at the j th stage.
$Q_{k,j}^{\text{max}}$	Maximum turbine discharge of hydroplant k at the j th stage.
$Q_{k,j}^{\text{min}}$	Minimum turbine discharge of hydroplant k at the j th stage.
$V_{k,j}^{\text{max}}$	Maximum storage of reservoir k at the j th stage.
$V_{k,j}^{\text{min}}$	Minimum storage of reservoir k at the j th stage.
$O_{k,j}^{\text{max}}$	Maximum total water discharge of hydroplant k at the j th stage.
$O_{k,j}^{\text{min}}$	Minimum total water discharge of hydroplant k at the j th stage.
h_j^{max}	Maximum total power output of hydropower system.
h_j^{min}	Minimum total power output of hydropower system.
E	Objective value to be optimized.
C_j^1	Residual load of power grid at the j th stage.
$V_{k,j}$	Storage volume of reservoir k at the j th stage.
$Z_{k,j}$	Forebay water level of reservoir k at the j th stage.
$I_{k,j}$	Total inflow of reservoir k at the j th stage.
$L_{k,j}$	Power output of hydroplant k at the j th stage.
$O_{k,j}$	Total discharge of hydroplant k at the j th stage.
$W_{k,j}$	Water spillage of hydroplant k at the j th stage.
$Q_{k,j}$	Turbine discharge of hydroplant k at the j th stage.

2.2. Objective function

Currently, the centralized scheduling mode is widely used in China, and operators are asked to make the generation plan of all plants for the next day so as to ensure safe and stable operation of power grid [8]. Recently, as the electricity demand increases rapidly, it is of great importance to make full use of flexible energy resources to respond to the loads at peak periods. Generally, with the merits of fast startup and shutdown, hydropower is able to provide sufficient spinning reserve, and is more independent than solar and wind power because it will not be influenced by day/night shift or weather conditions. As a result, hydropower is often preferred to smooth the peak loads in the power system of China. After subtracting the total output of hydroplants from the original load curve, the remaining load is then assigned to other kinds of

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