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Optimization of hydropower reservoirs operation balancing generation benefit and ecological requirement with parallel multi-objective genetic algorithm

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ABSTRACT

Recently, with increasing attention paid to energy production and ecological protection, the hydropower reservoirs operation balancing generation benefit and ecological requirement is playing an important role in water resource and power systems. Thus, the parallel multi-objective genetic algorithm is introduced to effectively resolve this multi-objective constrained optimization problem with two competing objectives and numerous physical constraints. In the proposed method, the original large-sized swarm is decomposed into several smaller subpopulations that will be simultaneously evolved on several computing units, effectively enhancing the execution efficiency and population diversity. During the evolutionary process, the chaotic initialization method is used to enhance the quality of initial population, while the feasible space identification method and the modified domination strategy are designed to improve the feasibility of solution and convergence rate of individuals. The results from the Wu hydropower system of China show that the presented method can make full use of computationally expensive resources to improve the performance of population. For instance, compared with the traditional method, the presented method can make 69.23% and 27.44% improvements in the standard deviation of power generation and water deficit in normal year, respectively. Thus, this paper provides an effective tool to support the multi-objective operation optimization of hydropower system.

1. Introduction

Hydropower is seen as one of the most important renewable energy with high operation flexibility in the power system [1]. Then, hydropower has been witnessing a booming period in the past decades [2], while a large number of reservoirs have been built around the world [3]. For instance, the number of large and medium-sized hydroplants under a single dispatching center in China is close to 200 [4]. Thus, the optimal operation of hydropower system is playing an increasingly significant role in electrical power system and water resources system [5]. Traditionally, the hydropower operation aims at determining the optimal water level or energy generation of all the hydroplants so as to maximize the total economic benefit of hydropower system [6]. This operational mode is easy to implement and has achieved varying degrees of success in practice [7]. However, reservoirs can not only bring about economic benefit but also have certain negative influences on natural hydrological regime of rivers [8]. The reason is that in some cases, reservoirs tend to keep water at a high level to operate at high efficiency zones and generate more electricity [9]. As a result, the minimum release constraints of downstream river channel are often violated, leading to the deterioration of ecological environment [7]. Recently, the ecological friendly operation for balancing environmental protection and economic benefit is becoming increasingly popular, which has gotten heightened attention from a variety of regulatory agencies [10]. In order to achieve this goal, many engineering or non-engineering measures have been widely studied to alleviate the adverse impact of ecological flow shortage [11]. The application results show that non-engineering measures have the merits of easy-implementation and low-cost in comparison with engineering measures represented by forest planting, fish way construction, river regulation and dredging [12]. As a famous

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non-engineering measure, the ecological operation is able to effectively balance generation benefit and ecological protection by dynamically adjusting the operation mode based on the actual working conditions of reservoirs [13]. Hence, this paper focuses on the optimization of hydropower reservoirs operation balancing generation benefit and ecological requirement (HROGE), which may provide potential technical reference for the operation of run-of-river hydroelectric stations.

Mathematically, the HROGE problem can be classified as a typical multi-objective optimization problem with two conflicting objectives and a group of complicated constraints, like water level constraints, power output constraints and water balance equations [14]. To address this problem, many effective optimization techniques have been proposed by researchers in the past decades [15]. On the one hand, from a decision-making point of view, those approaches can be divided into three groups [16]: the first is approaches with a priori articulation of preferences where the relative importance of objective functions are determined before running the optimization algorithm [17], like the weighted global criterion method, weighted sum method and goal programming methods; the second group is approaches for a posteriori articulation of preferences where a single solution is chosen from a set of mathematically equivalent solutions [18], like physical programming, normal boundary intersection method, normal constraint (NC) method [19]; the third is methods with no articulation of preferences where the decision-maker will continually provide input in the solution process of algorithms [20], like global criterion methods, Nash arbitration and objective product method. On the other hand, from the viewpoint of the problem-solving idea, those methods can be roughly divided into three different categories [21]: constraint method [22], single-objective method [23] and multi-objective method [24]. In the first group, the ecological flow is regarded as a constraint with certain admissible limit [25], which cannot provide enough information on the tradeoff front and may produce infeasible solutions in some cases (like extreme-drought years) [26]. In the second group, the ecological flow is treated as an optimization objective, and then some special strategies (like the weighting method, ideal-point method or sequential optimization method) are used to transform the HROGE problem into a single-objective optimization problem that will be solved by the existing methods (like dynamic programming or linear programming) [27]. The second group can only obtain one solution in a single run and often need to run many times to generate Pareto solutions [28]. Besides, the second category may fail to produce non-dominated solutions for problems with nonconvex Pareto front [29]. The third group uses multi-objective evolutionary algorithms (MOEA), multi-objective programming approaches (like fractional programming) and other methods to simultaneously optimize two or more competing objectives [30]. With the unique ability of discovering satisfying Pareto solutions for decision-makers, the third category is attracting more and more attention from researchers and scholars [31]. However, due to the premature convergence caused by the inherent defects in random search methods [32], MOEA may converge to unsatisfactory Pareto optimal fronts in some cases, which indicates that there are certain spaces to improve the search capability and population diversity [33]. Thus, it is necessary to develop some new optimization methods to resolve the HROGE problem.

With the rapid development of computer technology, the multi-core processors are becoming the standard configuration of personal computers, workstations and servers. The popularization of multi-core processor provides essential hardware foundations for parallel algorithms [34]. Besides, many parallel computing frameworks have been successfully developed by different companies or institutions, which can greatly promote the technical progress of parallel computing [35]. Generally, parallel computing is an effective way to improve the execution efficiency of compute-intensive tasks in comparison with the serial computation methods [36]. Hence, the parallel computing is enjoying unprecedented development opportunities in many research fields [35]. However, even to this day, there are still few literature about using the parallel technique to address the HROGE problem. To fill this gap, this paper is motivated to find the reasonable entry point between MOEA and parallel computing. Before realizing this purpose, there are two important steps requiring attention. The first key step is the choice of the serial methods to be parallelized since it has a direct influence on the obtained solutions [37]. Considering its good search capability and rapid running speed, the classical non-dominated sorting genetic algorithm-II (NSGA-II) is chosen for parallelization [38]. Another crucial step is to choose an appropriate parallel computing framework because it has an important effect on the performance of algorithm [39]. Considering that our previous NSGA-II method is encoded in Java language, Fork/Join becomes the first preferred tool used to parallelize algorithms. Then, a novel parallel multi-objective genetic algorithm (PMOGA) linking parallel technique into NSGA-II is introduced here. In PMOGA, the parallel technique is used to enhance the computation efficiency while the swarm decomposition strategy is employed to diversity the individuals. Besides, the chaotic initialization based on logistic map is employed to generate the initial swarm, while the two-stage identification strategy and the modified dominance relationship method are used to further improve the feasibility of solutions. The effectiveness of PMOGA is verified by several simulations in a real-world hydropower system.

To sum up, the key contributions and innovative applications of this paper lie in: (1) an effective multi-objective optimization model is presented for HROGE; (2) the novel PMOGA is introduced to solve the complex HROGE problem, where the population decomposition strategy and parallel computing technique are used to simultaneously improve the swarm diversity and execution efficiency; (3) the search space identification method and the modified dominance relationship are used to enhance the feasibility of solutions in the evolutionary process; (4) the presented method is applied to the real-world cascaded hydropower system in China, and the results of PMOGA outperforms the traditional multi-objective genetic algorithm (MOGA) in different cases, providing a practical tool to support the multi-objective operation of hydropower system.

The reminder of the paper is organized as below. Section 2 presents the mathematic model for HROGE. Section 3 introduces the PMOGA algorithm after the brief descriptions of NASGA-II and Fork/Join. Section 4 gives the details of PMOGA for the HROGE problem. Section 5 testifies the effectiveness of the proposed method, and then the conclusions are summarized in Section 6.

2. Mathematical modeling

In this section, the objective function and physical constraints involved in the HROGE problem are given in details. Generally, with limited water resources, the goal of HROGE in this research is to simultaneously obtain the maximization of the generation benefit and the minimization of the ecological water shortage in the scheduling horizon.

2.1. Objective function

(1) Objective 1: maximizing the total power generation

The first objective function is chosen to achieve the maximization of the total generation of all the hydropower plants during the