Hydropower system operation optimization by discrete differential dynamic programming based on orthogonal experiment design

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A B S T R A C T
With the fast development of hydropower in China, a group of hydropower stations has been put into operation in the past few decades and the hydropower system scale is experiencing a booming period. Hence, the “curse of dimensionality” is posing a great challenge to the optimal operation of hydropower system (OOHS) because the computational cost grows exponentially with the increasing number of plants. Discrete differential dynamic programming (DDDP) is a classical method to alleviate the dimensionality problem of dynamic programming for the OOHS, but its memory requirement and computational time still grows exponentially with the increasing number of plants. In order to improve the DDDP performance, a novel method called orthogonal discrete differential dynamic programming (ODDDP) is introduced to solve the OOHS problem. In ODDDP, orthogonal experimental design is employed to select some small but representative state combinations when constructing the corridor around the current trajectory, and then dynamic programming recursion equation is used to find an improved trajectory for the next iteration. The proposed method is applied to the optimal operation of a large-scale hydropower system in China. The results indicate that compared to the standard DDDP, ODDDP only needs about 0.37% of computing time to obtain the results with about 99.75% of generation in the hydropower system with 7 plants and 3 states per plant, providing a new effective tool for large-scale OOHS problem.

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1. Introduction

Hydropower, the power derived from the energy of falling and running water, hardly produce any environmental pollutants and is considered as one of the most important renewable energy at present [1–5]. Hence, many countries have been devoting to the development of hydropower [6], and a lot of hydro plants are put into operation successively in the past few decades [7–13]. From Fig. 1, we can find that in China, by the end of 2014, the total hydropower installed capacity is more than 300 GW and the share of hydropower is up to 22.2% installed capacity of all the energy and 68.3% installed capacity of all clean energy, respectively. Besides, the number of medium and large-sized hydropower plants operated by a central dispatching authority is close to 200 [13,14]. Furthermore, according to the “13th Five-Year Electrical development Plan” of this country, hydropower is given the first priority among all kinds of energy resources, and it is estimated that the total hydropower installed capacity of China will be about 380 GW in 2020, which is equal to the sum of hydropower installed capacity in other top seven countries [15–17]. Thus, the optimal operation of large-scale hydropower becomes one of the most important works in the economic operation of power grid in China. However, the large number of hydropower plants and rapid expansion of system scale is causing the serious “curse of dimensionality”, which has posed a tremendous challenge to the operators of electrical power system, especially in China [18–20].

Generally, the optimal operation of hydropower system (OOHS) aims at finding the best water level or power generation of all the hydropower plants so as to maximize the total system benefit in the entire scheduling horizon [21,22]. In the OOHS problem, a set of equality and inequality constraints must be considered in the modeling process, such as hydraulic and electric relationship among different plants, water balance equations, water level and water discharge limits. Hence, mathematically, OOHS is a multi-stage, nonlinear and high-dimensional optimization problem subjecting to a group of complicated constraints [23–25]. In order...
to efficiently solve the OOHS, many classical algorithms have been proposed and developed by researchers, including linear programming (LP), non-linear programming (NLP) [26], dynamic programming (DP) and heuristic evolutionary algorithms (HEA). Although various degrees of success have been achieved in the past years, there are still some shortcomings in these methods when handling large-scale OOHS problem. LP may produce large bias in the linearization procedure due to the existing nonlinearity of OOHS [27]. NLP is not appropriate for non-convex problems and its computational efficiency is not satisfactory in some cases [28]. For the OOHS in the practical engineering, HEA is mainly limited by the premature convergence problem and random oscillation of the final solutions [29]. Compared to the above methods, DP can efficiently address linear or nonlinear, convex or non-convex, and even discontinuous objective functions, as well as a variety of complicated constraints. Moreover, DP can obtain the global optimal solution in most cases. Thus, DP has been widely used in many fields, especially in water resources systems. However, DP suffers from the “curse of dimensionality” in large-scale complex system [30–32]. To address the dimensionality problem, several dynamic programming variants are proposed in the past years, such as dynamic programming successive approximation (DPSA) [33], progressive optimality algorithm (POA) [8] and discrete differential dynamic programming (DDDP) [34]. Even though these modified DP methods can reduce the dimensions to some extents, the computational burden may still be intolerable when the problem scale reaches a certain large degree [35,36]. Thus, DP has been widely used in many fields, especially in water resources systems. However, DP suffers from the “curse of dimensionality” in large-scale complex system [30–32]. To address the dimensionality problem, several dynamic programming variants are proposed in the past years, such as dynamic programming successive approximation (DPSA) [33], progressive optimality algorithm (POA) [8] and discrete differential dynamic programming (DDDP) [34]. Even though these modified DP methods can reduce the dimensions to some extents, the computational burden may still be intolerable when the problem scale reaches a certain large degree [35,36]. Thus, there are urgent needs to develop some new efficient ways to ensure the computational efficiency for large-scale hydropower systems [37–40].

In this paper, the calculation process of DDDP is analyzed and we find that its dimensionality problem lies in the comprehensive combinations of discrete state values of all hydro plants. From the perspective of experimental design, the comprehensive combination can be seen as a full-scale test, and it is almost impossible to do all the tests one by one in large-scale engineering problems. Thus, the orthogonal experiment design (OED) was developed for the purpose of reducing the number of combinations. OED takes full advantage of well-designed orthogonal arrays to select a subset of combinations for experimentation, rather than all the combinations [41,42]. As one of the most successful methods for multifactors multi-levels experiment, OED has been widely used in many different fields [43–45]. Thus, inspired by this idea, we use the OED to select some small but representative state combinations when constructing the corridor around the current trajectory in DDDP, which can simultaneously reduce the requirements of memory usage and consuming time. Then, a new method called orthogonal discrete differential dynamic programming (ODDDP) is presented, where OED is employed to restrict the search space of corridor while the dynamic programming recursion equation is used to gradually improve the quality of solution. Our method is applied to long-term operation of Guizhou hydropower system in China, and the results indicate in the 4-plant and 5-state hydropower system that, the proposed method can cut down about 98% of computing time but obtains solutions with 99.4% power generation when compared to DDDP, showing its competitive performances in both execution time and computational accuracy.

The reminder of the paper is organized as follows. Section 2 gives the optimization model of OOHS. Section 3 presents the ODDDP algorithm after the brief descriptions of DP, DDDP and OED. In Section 4, the proposed method is applied to a large-scale hydropower system in China. Finally, the conclusions are given in Section 5.

2. Mathematical modeling

2.1. Object function

Generally, the objective of hydropower system in the electricity market is to maximize the total benefit of all plants during the scheduling periods, which can be described as follows:

$$\max \ E = \sum_{k=1}^{K} \sum_{j=1}^{J} c_{kj} P_{kj} t_j, \quad P_{kj} = A_k Q_{kj} H_k$$  \hspace{1cm} (1)$$

where $E$ is the total benefit of hydropower system. $K$ is the number of hydro plants in system. $J$ is the number of periods. $c_{kj}$ is the electricity price of the $k$th hydro plant at the $j$th stage; when $\forall i, j, c_{kj} = 1$. Eq. (1) can be seen as the optimization model to maximize the total generation of hydropower system. $t_j$ is the total hours in the $j$th stage. $P_{kj}$, $Q_{kj}$ and $H_k$ are the power output, turbine water discharge and net water head of the $k$th hydro plant at the $j$th stage, respectively. $A_k$ is the power coefficient of the $k$th hydro plant.

2.2. Constraints

In the OOHS problem, the following equality and inequality constraints should be satisfied.
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