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Optimization of large-scale hydropower system peak operation with hybrid dynamic programming and domain knowledge

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ABSTRACT

With the rapid economic growth in recent years, the power demands in China keep growing and the need for reducing peak loads is becoming more prominent. With the merits of fast startup and shutdown, hydropower is often used to respond the peak load. In order to meet the practical requirement of peak operation in electrical power system, a novel min-max dynamic programming model is formulated for the peak operation of hydropower system. Then, the hybrid dynamic programming method is presented to alleviate the dimensionality problem in large-scale hydropower system, where the dynamic programming successive approximation is employed to divide the complex multi-dimensional problem into a series of small subproblems, and then the discrete differential dynamic programming is adopted to sequentially solve these subproblems. In addition, inspired by domain knowledge, the initial solution generation method and feasible space identification method are designed to promote the convergence speed of algorithm. The proposed method is used to solve the peak operation problem of a large-scale hydropower system in China. The simulations with different load demands indicate that the hybrid dynamic programming can achieve satisfactory performance in reducing peak loads of power system.

1. Introduction

With the fast economic development, the electricity demand of China grows relatively quickly in the past several decades (Yang and Lin, 2016). Taking one power grid in China as the example, the maximum electricity load has increased by about 5.6 times, from 4.63 GW in 2000 to 26.25 GW in 2015. The rapid growth of power load demand is posing a severe challenge to the managers and operators of hydropower system (Yu et al., 2016a). Among all the existing generators, the solar and wind turbine generator may be easily affected by the weather in nature (Beluco et al., 2012; Patsialis et al., 2016); the reaction rates per minute of steam and gas turbines are about 3% and 5%, far less than 50% of hydropower generators (Liu et al., 2017); hydropower generators only need about 3–5 min to provide 100% of power to respond the load changes (Kong et al., 2016). Due to its superior performance in load regulation and the merit of being clean (Hui et al., 2016), hydropower has developed quickly since 2000 in China (Ma et al., 2013). According to the State Statistics Bureau of China, the total installed capacity of hydropower was 320 GW by the end of 2015. As the scale of hydropower system expands, the number of hydropower plants and constraints will increase significantly (Huang et al., 2016), while the hydraulic and electric relationships among hydroplants also becomes more complex (Madani, 2011; Feng et al., 2017a). With the increasing operational complexity and optimization difficulty (Xie et al., 2010), the large-scale hydropower system peak operation (LHSPO) becomes one of the most important problems in many provincial and regional power grids, especially in China (Zambon et al., 2012).

Generally, the problem of LHSPO in China is characterized by the following features: (1) Large system scale. A large number of hydropower plants are connected to power grid and many more are in planning phase or under construction, and the total installed capacity of hydropower in a centralized control center often exceeds 10 GW (Zhou et al., 2015). For instance, there are eight hydroplants (11 GW) and sixteen hydroplants (25 GW) on the main stream of Wu River and Dadu River, respectively. Besides, the capacity of hydro turbines unit are remarkably enhanced while the 300 MW–700 MW of unit capacity has been widely used in many

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hydroplants of China (Cheng et al., 2012). For instance, the hydro turbine with 700 MW capacity was installed in Three Gorges project. (2) Complex operation constraints. Except for the security constraints of hydroplants and power grids, there are also close hydraulic and electric connection between upper and downstream hydroplants (Zhang et al., 2014), while many other factors (like flood control, power generation, environmental protection and navigation) should be considered in the modeling process (Li et al., 2014a, b), which will no doubt increase the number of constraints. (3) Huge peak load pressures. The difference between peak and valley is becoming bigger and bigger, which has posed difficulties on the peak operation of power system (Feng et al., 2018). In addition, the new energy sources (like wind energy and solar energy) may generate electricity at valley periods (Zhen et al., 2016), which may further increase the difficulty of peak operation (Blokhuis et al., 2011; Wu et al., 2016). Thus, hydropower needs to quickly respond the dynamic change or fluctuation of load demand, especially in coal-dominated energy system.

As a result, the objective for hydropower system peak operation is to determine the optimal scheduling process of all hydropower plants so as to smooth the residual load series as much as possible (Blokhuis et al., 2011), while satisfying indispensable operational constraints imposed on both hydropower system and reservoirs (Chen et al., 2014). Mathematically speaking, the LHSPO problem can be classified as a complex large-scale nonlinear constrained optimization problem (Nabavi-Pelesaraei et al., 2017). As an optimization problem with important practical engineering values, a great deal of attention has been paid by researchers all over the world (Yeh, 1985; Yu et al., 2016b), and many effective models and methods have been proposed to resolve this kind of problem (Rani and Moreira, 2010). For instance, the quadratic programming is used to determine the quarter-hourly generation schedules allocated for several provincial power grids, where the minimization of the variance of remaining load is chosen as the objective (Shen et al., 2014); to reduce the peak load at home area, a linear programming model is developed to solve the power consumption operation problem of ESS (Energy Storage System) and V2G (Vehicle to Grid) (Lee and Choi, 2014); to simultaneously reduce the peak loads of multiple power grids, a local search method is presented to handle with the multi-objective short-term hydropower scheduling model developed for China Southern Power Grid (Wu et al., 2015); to smooth the remaining load series of multiple power grids, a three-step hybrid algorithm based on heuristic search strategies is proposed for day-ahead peak schedules of pumped storage power plants (Cheng et al., 2015); to obtain the optimal peak operation of hydroplants, a hybrid method is presented to address the benefit-maximization model considering the peak shaving constraints (Xie et al., 2016), and it should be pointed out that “peak shaving” denotes the “reduction the peak load of power system”; by including peak generation as decision variables, an optimization model is presented to better operate hydroplants in long-term hydrothermal system operation planning problem (Brandi et al., 2016); to meet the practical requirement of peak shaving operation, a linear programming method is proposed to find the optimal quarter-hourly generation allocation plan (Feng et al., 2017b). Even though various degrees of successes have been achieved, there are still some disadvantages in these above methods (Labadie, 2004; Zhou et al., 2014; Wang et al., 2017). Linear programming may produce certain calculation errors on the final solution due to the linearization or piecewise linearization of nonlinear objectives or constraints (Cai et al., 2001). Nonlinear programming cannot effectively handle non-convex optimization problems and its computational burdens may be intolerable in some cases (Catalão et al., 2010). Intelligence algorithms are limited by the problems of premature convergence and instable solutions (Mu et al., 2015). Heuristic search strategies depend on the preset specific rules and may fall into locally optimal solution with a high probability (Chau, 2007; Feng et al., 2017c). Therefore, there is practical requirement to develop effective methods for reducing the peak loads of power grids.

A natural approach for the LHSPO problem is to model the system as a dynamic programming (DP) model because this method can efficiently deal with the linear and nonlinear characteristic of objectives and constraints (Catalão et al., 2012), and obtain global optimal solution in the discrete state space (Zhao et al., 2012a). However, the commonly-used objective for LHSPO is to minimize the variance of left load series that is obtained by subtracting the total generations of all the hydroplants from the original load curves (Shen et al., 2015). The result derived from this optimization objective is closely related with the values of residual load series, which is tightly coupled with the scheduling periods. Due to the inseparability of this objective, it is often difficult for DP to directly solve the LHSPO problem. In order to overcome the above-mentioned defect, it was found that the above nonlinear objective function of the LHSPO problem can be converted into a linear one which is the minimization of the maximum value of remaining load series. Then, a min-max DP recursive equation is formulated for the complex LHSPO problem. However, when addressing high-dimensional optimization problems, the classical dynamic programming method will suffer from the severe dimensionality problem, resulting in not only long execution time but also high memory usage (Madani and Lund, 2011). In other words, the traditional dynamic programming method cannot satisfy the practical requirements of the LHSPO problem. Hence, for the sake of alleviating the dimensionality problem, a novel method known as hybrid dynamic programming (HDP) is presented here to improve the computational efficiency. In the HDP, the idea of dynamic programming successive approximation (DPSA) is firstly employed to divide the large-scale hydropower system into a sequence of subproblems, and then the discrete differential dynamic programming (DDDP) is used to solve these subproblems. Besides, based on the domain knowledge, the initial solution generation method and feasible search space identification method are incorporated into the hybrid dynamic programming so as to ensure the feasibility of solutions. The simulations demonstrate the effectiveness of the HDP approach.

To clearly understand the contribution of this paper, the main work is summarized as below: (1) after deeply analyzing the objective to be optimized, a novel min-max DP model is formulated for LHSPO. (2) To handle the dimensionality problem in the traditional DP method, the HDP method linking DDDP with DPSA is presented. (3) To improve the performance of algorithm, the domain knowledge is used to dynamically generate the initial solution and effectively identify the feasible space during the optimization process. (4) The proposed algorithm can obtain satisfactory results in different cases, providing a new alternative to alleviate the peak loads pressure of power grid.

The rest of this paper is organized as below. Section 2 gives the mathematical model of the LHSPO problem. Section 3 presents the min-max DP model for LHSPO. Section 4 gives the ideas of the HDP algorithm after the descriptions of DDDP and DPSA. The details of HDP for solving the complex LHSPO problem are given in Section 5. Then, HDP is applied to resolve a real-world hydropower system of China in Section 6. Finally, the conclusions are summarized in Section 7.