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Developing a successive linear programming model for head-sensitive hydropower system operation considering power shortage aspect

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ABSTRACT

The power industry is playing an increasingly important role in the world economy, and insufficient power supply may lead to huge enormous economic loss throughout the world. Then, the problem of power shortage is receiving a great deal of attention from operators and managers in electrical power system. With the merits of fast startup-shutdown, hydropower is regarded as one of the most reliable renewable energy sources to smooth the electricity shortage of power grid. Thus, this paper focuses on the operation of head-sensitive hydropower system considering power shortage aspect. To effectively address this problem, a novel method based on linear programming and successive approximation is proposed, where the initial hydraulic heads of each hydroplants is generated based on the actual working condition, and then the linear programming method is used to solve the fixed-head hydropower optimization problem involving a carefully-designed min-max optimization objective, while the successive approximation strategy is employed to incrementally improve the solution's quality by dynamically updating water heads of all the hydropower plants. The simulations demonstrate that compared with the original load demand, our method can make an average of approximate 20% reduction in electricity shortage of power system, demonstrating its effectiveness and practicability.

1. Introduction

In recent years, with the steady promotion of the modernization process, the energy industry is playing an increasingly significant role in promoting the world economic development in a healthy and ordered way [1,2]. Taking the world's second largest economy as an example, the data from the State Statistics Bureau of China shows that the nationwide energy consumption has increased from 0.6 trillion kilowatt-hours in 1990 to 5.6 trillion kilowatt-hours in 2014. However, the electricity supply may fall short of power demand due to some reasons [3–5], like limited installed electricity capacity, uneven distribution of electric power sources, unreasonable industrial structure, and low energy production efficiency. As a result, tremendous economic losses will be inevitable when the problem of power shortage happens [6]. For instance, in the early 20th century, a single province of China has suffered from hundreds of electricity cuts and billions of dollars' economic losses caused by power shortage per year on average; while a great number of developing countries are facing with similar problems at the present stage [7]. To reduce the negative influence of power deficit, a more practical and manageable way is to improve the operation efficiency of power plants in the interconnected power system [8]. Among all the energy resources, hydropower is regarded as one of the most mature and reliable renewable energy at the present stage [9–11]. Due to its unique advantages in lower pollutant discharge and high speed in start/stop, hydropower is given a high dispatching order in the energy-saving generation dispatch released by the National Development and Reform Committee of China [12,13]. Thus, this paper focuses on the operation optimization of head-sensitive hydropower system considering power shortage aspect.

Mathematically, the problem of head-sensitive hydropower

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system operation considering power shortage aspect can be categorized as a multi-stage constrained optimization problem subjecting to a set of complicated equality and inequality constraints [14–17], like water balance equations and power output limits. In the past few decades, many effective optimization approaches have been developed to resolve this kind of problem [18–23], which can be roughly divided into two different groups: one is the classical mathematical programming methods, like linear programming (LP) [24–26], nonlinear programming [6,27–29] and dynamic programming [30–32]; while the other is modern evolutionary algorithms, like genetic algorithm [33,34], particle swarm optimization [35], differential evolution [36] and cuckoo search algorithm [37]. Although dynamic programming can effectively handle with the hydropower operation problem, the well-known dimensionality problem limits its application in large-scale hydropower system [38]. For nonlinear programming, it may fail to provide feasible solutions within reasonable execution time in some cases, like indefinite quadratic programming problems [39]. Inspired by biological evolution and cooperative behavior in nature, modern evolutionary algorithms use the stochastic search strategy to search for an improved solution in the decision space. However, due to the premature convergence problem, the results obtained by evolutionary algorithms are often instable at different independent runs [40–43], which cannot satisfy the reliability requirement of production departments. Compared to the above methods, linear programming can guarantee the globally optimal solution when the objective and constraints are linear functions of decision variables [44–46]. However, the intrinsic nonlinearity of hydroplants (like stage-storage curve and power generation characteristic) makes it become a complex nonlinear optimization problem with the strong spatiotemporal coupling features [47–49]. Obviously, when using the traditional modeling way, it is difficult or even impossible to directly apply the linear programming to address the focused problem. Then, in order to overcome the above drawbacks, a novel successive linear programming model is developed in this paper to satisfy the practical requirement of reducing electricity shortage in power system.

After deeply analyzing the problem characteristics, it was found that when the water heads of all the hydroplants are fixed, the goal of reducing power electricity can be guaranteed by taking the minimization of the maximum value of the residual load series as the objective function, while all the physical constraints (like water balance equations, power output or storage volume constraints) can be indicated by the linear equality or inequality functions of decision variables. Based on the well-designed constraint transformation technique and min-max objective function, the problem of fixed head hydropower system operation considering power shortage aspect becomes a standard linear programing problem that can be solved by existing optimizer. Then, the nonlinear generation characteristics and head sensitivity of hydropower system can be successively approximated by optimizing a sequence of subproblems with dynamically updated hydraulic head. Besides, based on the working condition of hydropower system, a practical heuristic strategy is presented to estimate the possible initial water heads of all the hydroplants from upstream to downstream, guaranteeing the quality of initial solution. The effectiveness of the LP model is successfully proved by several simulations from a real-world hydropower system of China. Finally, to better understand this paper, the contributions are summarized as below: (1) to satisfy the actual demand of power system, a min-max optimization objective is carefully designed for head-sensitive hydropower system operation considering power shortage aspect; (2) the successive linear programming model is presented for the practical problem, where the initial working condition of each plant is estimated and then the linear programming model based on constraint integration is employed to resolve the fixed-head hydropower operation problem, improving the quality of solution via the successive approximation technique; (3) the simulation results indicate that the presented model can achieve approving performance in reducing the electricity shortage of power system, providing an effective tool for head-sensitive hydropower system operation with power shortage aspect.

The reminder of this paper is organized as below. Section 2 describes the objective function and operation constraints for the hydropower operation problem. Section 3 shows the recent research work. The details of the LP model for the fixed-head and head-sensitive hydropower operation problem are given in Sections 4 and 5, respectively. The effectiveness of the LP model is proved in Section 6. Finally, the conclusions are summarized in Section 7.

2. Mathematical modeling

2.1. Problem analysis and objective function

In the ideal case, there are enough installed capacity of electricity in power system to satisfy the economic development requirements, and the dynamic balance between electric supply and energy demand can be strictly achieved at each scheduling period, which indicates the problem of power shortages will be no longer in existence. However, the electricity deficit problem may be inevitable in some special circumstances (like booming economy and natural disasters). Then, it is necessary for operators to take the problem of electricity shortage into consideration. When hydropower is used to provide generation, the residual load series is obtained by subtracting the total generation of all the hydroplants from the original load demand curve. Then, a smooth residual load series will be conducive to keep the scheduling continuity of the electric-consuming departments and power generation enterprises, thereby making a significant improvement on the operational efficiency of power system [50]. To achieve this goal, the minimization of the variance of remaining load curve (MVRLC) is often chosen as the objective function [51], which has been wildly used in the daily dispatching of power grid in China. However, due to irrational setting of computational parameters or constraints, the objective function derived from MVRLC may become an indefinite quadratic programming problem in practice, and the global optimal solution cannot be theoretically obtained by local optimization procedures in polynomial time. Hence, it is important to search for a more effective modeling technique to handle with this problem.

Supposing that all the hydroplants increase power generation at peak-load periods and raise water level to store energy at valley-load periods, the residual load curve will gradually become a flat one because the peak loads are sharply reduced while the valley loads remain unchanged. In addition, the residual load curve will become a straight line when there is no any difference between peak loads and valley loads. In other words, reducing the peak values of residual loads is a feasible way to smooth the residual load curves, which accords with the actual situation of many power grids in China. The smaller the maximum residual loads, the better the performance of reducing electricity shortages. Thus, based on the above analysis, the objective function is chosen to minimize the maximum value of the residual load series, which can be expressed as below:

$$F = \min\left\{ \max_{1\le j\le T}\left\{ D_j - \sum_{i=1}^{N} P_{i,j} \right\} \right\} \tag{1}$$

And the power output is considered as a nonlinear function of