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Short-term optimal operation of Three-gorge and Gezhouba cascade hydropower stations in non-flood season with operation rules from data mining

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ABSTRACT

Information hidden in the characteristics and relationship data of a cascade hydropower stations can be extracted by data-mining approaches to be operation rules and optimization support information. In this paper, with Three-gorge and Gezhouba cascade hydropower stations as an example, two operation rules are proposed due to different operation efficiency of water turbines and tight water volume and hydraulic relationship between two hydropower stations. The rules are applied to improve optimization model with more exact decision and state variables and constraints. They are also used in the population initiation step to develop better individuals with culture algorithm with differential evolution as an optimization method. In the case study, total feasible population and the best solution based on an initial population with an operation rule can be obtained with a shorter computation time than that of a pure random initiated population. Amount of electricity generation in a dispatch period with an operation rule also increases with an average increase rate of 0.025%. For a fixed water discharge process of Three-gorge hydropower station, there is a better rule to decide an operation plan of Gezhouba hydropower station in which total hydraulic head for electricity generation is optimized and distributed with inner-plant economic operation considered.

1. Introduction

In China, Three-gorge and Gezhouba cascade hydropower stations is the biggest power source. It is also a huge electricity transmission point of the west to east power transmission project. After impoundment of Three-gorge reservoir, how to make a good schedule plan of this cascade hydropower stations in non-flood season to maximize the generated energy and the revenue given by power selling or ancillary services supply is an important focus [1–3]. Gezhouba reservoir plays a role of reverse regulation for Three-gorge hydropower station (TGHS) with a daily regulation capacity of 0.086 billion cubic meters. Its upstream water level is one decision factor of tail water level of TGHS in non-flood season. Gezhouba hydropower station (GHS) has 19 water turbines of 125 MW and 2 of 170 MW. TGHS has 26 water turbines of 700 MW rated capacity (it does not include six water turbines in the underground powerhouse) with higher operation efficiency than that of water turbines in GHS. Due to tight water volume and hydraulic relationship and different operation characteristics of water turbines, operation of Three-gorge and Gezhouba cascade hydropower stations can be concluded into two hierarchical problems. One is to determine water discharge processes for a given time horizon to develop total hydraulic head distribution. The second is to make water distribution and unit commitment plan for a fixed water discharge process. A better method for this complex problem is still being proposed.

Short-term electricity dispatch is a spatial and temporal continuous multi-stage decision-making process with complicated constraints, in which dimension of decision variables is dependent on the number of water turbines and temporal interval of decision-making. In the last several decades, feasible models and optimization methods are two focuses with persistent considerable efforts for an improvement. Intensive research on well application of models and their methods is done to narrow the gap between theoretical developments and real-world implementations. Classical mathematical programming methods, such as non-linear programming, dynamic programming and progressive optimization algorithm, have been widely used for it with relative simple models and constraints [4–8], in which curse of dimensionality is a main difficulty to be solved. Requirement on the characteristics of the optimization problem is a hindrance to an application of mathematical programming methods to short-term optimal operation of a hydroelectric system. So, simplifications and approximations as linearization and polynomial fitting, and other improved methods are proposed [9–11]. In the recent 20 years, attention has been gradually paid to the

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application of artificial and computational intelligence approaches, such as genetic algorithm [13–16], artificial neural network [17,18], particle swarm optimization [19,20], culture algorithm [29,30] and so on [12,21]. Those approaches are based on mechanism of random probability search without limitation on the characteristics of the optimization problem. But whether they are feasible and whether global best solutions can be developed by them should be still proved and tested by real cases. In my opinion, optimization methods are just tools. A pragmatic optimization model is the most important thing. For a cascade hydropower stations, there are two kinds information sources for operation decision. The first one is internal data, such as operation efficiency of water turbines, regulation capacity of a reservoir and water volume and hydraulic relationship between two hydropower stations. The other is historical data, such as inflow and water discharge of a reservoir and load demand from grids. Information hidden in them can be mined to form operation rules and to develop a better model with more exact decision and state variables and constraints [22–24]. Both of them are an improvement for operation decision. So, in this paper, short-term optimal operation of Three-gorge and Gezhouba cascade hydropower stations in non-flood season is developed with operation rules from data mining.

This paper is organized as follows. In Section 2, numerical model is developed with emphasis on electricity generation role of TGHS. Operation rules and new constraints are proposed by data mining in Section 3. Culture algorithm with difference evolution is chosen as the optimization method in Section 4 with a test function. Case study is developed in Section 5. Conclusion and discussion are finally given in Section 6.

2. Numerical model

In numerical model, all parameters are represented by upper capitals and all variables by lower capitals.

2.1. Objective function

The model proposed aims at maximizing the sum of electricity generation over a whole dispatch period. Formally, this is represented by the objective function as Formula (1).

$$F = max\left(\sum_{t=1}^{T}\sum_{j=1}^{J}p_{t,j}^{sx} + \sum_{t=1}^{T}\sum_{j=1}^{J1}p_{t,j}^{gx} + \sum_{t=1}^{T}\sum_{j=1}^{J2}p_{t,j}^{gd}\right) \quad (1)$$

where T is the number of intervals. J, $J1$ and $J2$ are numbers of water turbines in TGHS and GHS. $p_{t,j}^{sx}$ is the output of turbine j at interval t in TGHS, MW. $p_{t,j}^{gx}$ and $p_{t,j}^{gd}$ are the output of turbine j with 125 MW or 170 MW rated output at interval t in GHS, MW.

Output of turbine j at interval t is computed by a linear interpolating function represented by Formula (2). According to water discharge of turbine j (that is $q_{t,j}$) and hydraulic head (that is h_t) at interval t, bound data for interpolation are fixed. Bound hydraulic heads are represented by H^u and H^l. Water discharges and outputs in bound hydraulic heads are represented by $Q_1^l, Q_1^u, Q_2^l, Q_2^u$ and $P_{Q1}^l, P_{Q1}^u, P_{Q2}^l, P_{Q2}^u$.

$$\begin{aligned} p_{t,j} = &\left[P_{Q1}^l + \left(\frac{q_{t,j} - Q_1^l}{Q_1^u - Q_1^l}\right)\left(P_{Q1}^u - P_{Q1}^l\right)\right] \\ &+ \left\{\left[P_{Q2}^l + \left(\frac{q_{t,j} - Q_2^l}{Q_2^u - Q_2^l}\right)\left(P_{Q2}^u - P_{Q2}^l\right)\right]\right. \\ &- \left.\left[P_{Q1}^l + \left(\frac{q_{t,j} - Q_1^l}{Q_1^u - Q_1^l}\right)\left(P_{Q1}^u - P_{Q1}^l\right)\right]\right\}(h_t - H^l)/(H^u - H^l) \end{aligned} \quad (2)$$

In case study, data matrix of water discharge in combined conditions of hydraulic head and output is formulated firstly for three different water turbines. For TGHS, 26 water turbines are manufactured by four factories. There are 12 water turbines, Nos. 4–6, 10–14 and 19–22, manufactured by ALSTOM. There are six water turbines, Nos. 1–3 and 7–9, manufactured by VGS. The other eight water turbines are manufactured by Harbin Electric Machinery Company and Dongfeng Electric Machinery Company in China with the technology introduction and absorption from ALSTOM or VGS. In our study, only operation characteristics of water turbines by ALSTOM and VGS are provided. There is no more than one percentage difference in operation efficiency under different combined conditions of output and hydraulic head between the two water turbines. Therefore only operation characteristics of water turbines by ALSTOM are applied in computation.

2.2. Constraints

Bounding of variables and parameters, and the relationships among flow, volume and turbines status can be modeled through the following constraints.

Constraints (3)–(5) establish lower and upper bounds on water discharge of three kinds of water turbines. Emphasize is that upper bounds in above constraints are functions of hydraulic head for electricity generation. Constraints (6)–(8) define unit commitment rules, in which continuous on-line/off-line time can be fixed according to operation demand of a real case. In these constraints, unit statuses are classified into five categories based on $w_{t,j}^{sx,on}$ and $w_{t,j}^{sx,off}$ [25]. Constraints (9) and (10) establish lower and upper bounds on water level and water volume of the two reservoirs. Constraints (11) and (12) introduce water balance of two reservoirs within two consecutive intervals. There is a 30 min time delay originating from the non-steady flow of water discharge of TGHS. According to the contrast, it is found that there is just a little difference in water level process of Gezhouba reservoir with time delay considered or not. Therefore time delay is ignored. Constraints (13) and (14) introduce lower limit of mean diurnal water discharge of two hydropower stations. Constraints (15) and (16) indicate tail water level functions of two hydropower stations. Constraint (17) sets the final water level (water volume) to the desired target value at the end of the dispatch period due to daily regulation capacity of Gezhouba reservoir and reverse regulation role of GHS.

$$Q_{min}^{sx} \leqslant q_{t,j}^{sx} \leqslant Q_{max}^{sx} \quad (3)$$

$$Q_{min}^{gx} \leqslant q_{t,j}^{gx} \leqslant Q_{max}^{gx} \quad (4)$$

$$Q_{min}^{gd} \leqslant q_{t,j}^{gd} \leqslant Q_{max}^{gd} \quad (5)$$

where $Q_{max}^{sx}, Q_{max}^{gx}$ and Q_{max}^{gd} are the maximum water discharge of three kinds water turbines in TGHS and GHS, m^3/s. $Q_{min}^{sx}, Q_{min}^{gx}$ and Q_{min}^{gd} are the minimum water discharge, m^3/s. $q_{t,j}^{sx}$ is the discharge of water turbine j at interval t in TGHS, m^3/s. $q_{t,j}^{gx}$ and $q_{t,j}^{gd}$ are the discharge of water turbine j with 125 MW or 170 MW rated output at interval t in GHS, m^3/s.

$$\left(w_{t,j}^{sx,on} - T_{min-on}^{sx}\right)\left(s_{t-1,j}^{sx} - s_{t,j}^{sx}\right) \geqslant 0 \quad (6)$$

$$\left(w_{t,j}^{sx,off} - T_{min-off}^{sx}\right)\left(s_{t,j}^{sx} - s_{t-1,j}^{sx}\right) \geqslant 0 \quad (7)$$

$$-1 \leqslant \left(s_{t,j}^{sx} - s_{t-1,j}^{sx}\right) \leqslant 1 \quad (8)$$

where $s_{t,j}^{sx}$ is the operation status of water turbine j at interval t in TGHS, 1 is on, and 0 is off. T_{min-on}^{sx} and $T_{min-off}^{sx}$ are the minimum continuous on-line time and off-line time of water turbines in TGHS,