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Total output operation chart optimization of cascade reservoirs and its application

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ABSTRACT

With the rapid development of cascade hydropower stations in recent decades, the cascade system composed of multiple reservoirs needs unified operation and management. However, the output distribution problem has not yet been solved reasonably when the total output of cascade system obtained, which makes the full utilization of hydropower resources in cascade reservoirs very difficult. Discriminant criterion method is a traditional and common method to solve the output distribution problem at present, but some shortcomings cannot be ignored in the practical application. In response to the above concern, this paper proposes a new total output operation chart optimization model and a new optimal output distribution model, the two models constitute to a double nested model with the goal of maximizing power generation. This paper takes the cascade reservoirs of Li Xianjiang River in China as an instance to obtain the optimal total output operation chart by the proposed double nested model and the 43 years historical runoff data, progressive searching method and progressive optimality algorithm are used in solving the model. In order to take the obtained total output operation chart into practical operation, mean value method and stepwise regression method are adopted to extract the output distribution ratios on the basis of the optimal simulation intermediate data. By comparing with discriminant criterion method and conventional method, the combined utilization of total output operation chart and output distribution ratios presents better performance in terms of power generation and assurance rate, which proves it is an effective alternative method to deal with the cascade reservoirs joint operation problem.

1. Introduction

Hydropower is the only clean energy source that can be commercially developed on a large scale [1]. Compared with other energy sources, hydropower enjoys exceptional advantages [2], such as pollution-free, renewable and manageable. Moreover, hydropower has the unique ability to change output quite fast, which makes it good at meeting the changing demands for electricity and maintain the balance between supply and demand [3].

With the increasing development of cascade reservoirs, the joint operation optimization research of cascade reservoirs is attracting the attentions of many scholars all over the world [4]. It is a multi-variable coupled and complicated nonlinear programming problem [5], which needs to consider not only the hydraulic and electrical connection between upstream and downstream reservoirs, but also a lot of constraints. It has the characteristics of high dimensionality, strong coupling, and uncertainty etc [6].

Although many optimization models and methods are applied in reservoir operation [7–9], but the optimal decision-making of reservoir operation over the entire planning horizon is very difficult, what can we have is just a review of the happened operations [10]. In actual reservoir operations, whether the long-term, middle-term or the real-time, they all rely on the established operation rules due to the natural uncertainties of the predicted inflow [11,12], it is practical and operational to pursue better optimization or satisfactory solution by the established operation rules. Reservoir operation rules are intended to guide operation management of cascade reservoirs system so that the releases made are in the best interests of the system's objectives consistent with certain inflows and existing storage levels. These predefined operation rules are usually presented in the form of graphs and tables [13,14].

Several types of reservoir operation rules have been previously researched. In 1969, Revelle et al. [15] first introduced the linear decision rule, assuming that releases were linearly related to reservoir storage and decision parameters. Based on linear regression analysis, Karamouz and Houck [16] developed the reservoir operation rules by a deterministic optimization model, in which

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the correlation between the general operating rules and the optimal deterministic operation was being increased by going through an iterative process. Lund and Guzman [17] reviewed a variety of derived single-purpose operating policies for reservoirs in series and in parallel for water supply, flood control, hydropower, water quality, and recreation. Such rules were useful for real time operations, conducting reservoir simulation studies for real-time, seasonal, and long-term operations, and for understanding the workings of multi reservoir systems. Consoli et al. [18] used correlation analyses for developing monthly reservoir operation rules. They did regression analysis between monthly reservoir releases and the state variables of reservoir system. Malekmohammadi et al. [19] used a Bayesian Network for developing monthly operation rules for a cascade reservoirs system which was mainly aimed to control floods and supply irrigation needs, and Bayesian Network was trained and verified using the results of a reservoir operation optimization model, which optimized monthly releases from cascade reservoirs. Due to the different operation efficiency of water turbines and tight water volume and hydraulic relationship between Three-gorge and Gezhouba hydropower stations, Ma et al. [20] proposed two operation rules which were applied to improve optimization model with more exact decision and state variables and constraints. Ji et al. [21] used Support Vector Regression (SVR) to derive optimal operating rules, parameters in SVR model were calibrated with grid search and cross validation techniques to improve the performance of SVR. By considering both generalization and regression performance, the trained SVR model overcomes local optimization and over fitting deficits. Another operation rule is the Standard Operating Policy (SOP), which is referred to as the S-shaped curve of operation [22]. The principal idea of this SOP is to release as much water as the reservoir can provide to meet the target delivery.

Reservoir operation rules are varied, but the most frequently used at present is the reservoir operation chart, it mainly consists of different guide curves and corresponding operation zones. The widely accepted and used traditional reservoir operation chart at present is usually obtained through a reverse calculation by using the hydrological runoff data of typical years, and it has already received different degrees of success in different reservoir operations. But its disadvantages cannot be ignored, for example, the large complexity and randomicity of the calculation method, and the repeated empirical inspection and correction [23]. Moreover, it is very hard to achieve the global optimal solution, and more difficult to deal with the complex problems that contains multi-objective or multi-dimensional variables [24]. Thus, many scholars explored the optimization for reservoir operation charts, but the researches that have been done were mostly concentrated in the single reservoir operation chart, and little achievements about the cascade reservoirs operation chart were obtained. With the rapid development of cascade hydropower stations in recent decades, the cascade reservoirs system composed with multiple reservoirs needs unified operation and management to improve the utilization efficiency of water resources. However, because of the lack of in-depth study on joint optimization operation charts and output distribution method of cascade reservoirs, the hydropower resources of cascade reservoirs are very difficult to get full utilization [25]. The output distribution method presently used is the discriminant criterion method, but it is found that this method has some limitations in practical application. Therefore, the implementation of the joint operation method research for cascade reservoirs, especially the formulation of output distribution rules that corresponding to the cascade joint operation charts, has very important practical significance for guiding the cascade reservoirs operation.

Cascade total output operation chart optimization aims at getting the optimal operation chart of cascade system by the reasonable optimization model, with the goal of maximizing the total power generation over the entire planning horizon. Whether the ultimately gained operation chart is reasonable or not is determined by the output distribution method adopted in the optimization. Taking the cascade reservoirs of Li Xianjiang River in southwest China as the research object and considering the deficiencies of the discriminant criterion method in the application of cascade reservoirs operation, this paper proposed a new total output operation chart optimization model and a new output distribution model, these two models were used at the same time in the simulation calculation and constituted to a double nested model with the goal of maximizing power generation. The output distribution model used in operation chart optimization can not only give the output distribution of current stage, but also make the distribution results of this stage doing the optimal impact on subsequent stages, which will make the final power generation of all operation stages to be the best, while the other feasible alternatives cannot provide this global optimal impact, although they can give the output distribution of current stage. The output of the double nested model was the total output operation chart and the optimal simulation intermediate data of cascade system. In order to take the obtained total output operation chart into practical operation, mean value method and stepwise regression method were used to extract the output distribution ratios on the basis of the optimal simulation intermediate data. Stepwise regression method is a widely used practical method in data mining, which can be easily implemented in Matlab. Moreover, this method can automatically eliminate variables that are not important in regression, so it is more appropriate and effective to be used in extracting the output distribution ratios than other methods, such as cluster analysis, principal component analysis, and support vector regression, etc.

The following part of this paper is organized as follows. Section 2 presents the rationale and defects of discriminant criterion method in the application of cascade reservoirs operation, and explains the double nested model, including the total output chart optimization model and the optimal output distribution model. Section 3 shows the application of the proposed double nested model to the cascade reservoirs of Li Xiangjiang Basin in southwest China, and the optimization results are presented. In Section 4, the results are analyzed and discussed. Finally, the conclusions of this study will be provided in Section 5.

2. Methodology

2.1. Discriminant criterion method

2.1.1. Rationale of discriminant criterion method

Obviously, for a cascade system, there is an equation: $N_q = \sum N_j$, where N_j is the output of the jth hydropower station, N_q is the total output of cascade system, and there are countless combinations of N_j when the N_q is fixed, but there must be an optimal combination that can maximize the residual energy storage of cascade system at the end of an operation stage.

According to discriminant criterion method, the basic principle of guiding cascade reservoirs operation is to maximize the power generation and minimize the power loss as far as possible, the order of storing water or supplying water for reservoirs is determined and the optimization goals are achieved by this principle. Compared with the conventional operation schemes, this method can increase the reliability of power generation and improve the benefits of water resource utilization at the same fixed guaranteed output of cascade system, it is a relatively matured joint operation method in guiding cascade reservoirs operation at present [26].