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Research and application of key technologies in drawing energy storage operation chart by discriminant coefficient method

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A B S T R A C T

Discriminant coefficient method (DCM) is a traditional method in guiding the cascade reservoirs joint operation, but it cannot be well used directly in the practical application. This paper combined DCM with the cascade reservoirs energy storage operation chart (CRESOC) and proposed a new DCM based drawing model. In addition, three key technologies in the drawing process and one key technology in the practical application were studied emphatically, which can realize the combined utilization of DCM and CRESOC perfectly. In the case study, we took the cascade reservoirs of Li Xianjiang River in southwest China as an instance to study the CRESOC by the proposed drawing model. Compared with the existing single reservoir operation charts, the simulation results show that the CRESOC presents better performance in terms of power generation and assurance rate, especially on the latter, which has a growth of 6.8%. Moreover, in order to eliminate the insufficient of DCM in practical application, the boundary control curves of each reservoir for water storage and water supply were optimized by the proposed optimization technique, and the simulation results show that there is no water abandonment in all the 43 dry seasons after the optimization.

1. Introduction

With the increasing development of cascade reservoirs, the cascade reservoirs joint operation research is getting the attentions of many scholars all over the world [10,12,39]. In the actual reservoir operation, especially in the long and middle term operation, established operating rules are depended due to the natural uncertainties of inflow [7,38]. It is practical and operational to pursue second-best or satisfactory solution by the established operating rules [4,22].

Reservoir operating rules are varied [16,23,34,40], but the most frequently used at present is the reservoir operation chart [5] which is the graphical representation of reservoir operating rules, and it mainly consists of several operation curves and the corresponding operation zones. Reservoir operation chart is direct and concise, and it can make the reservoir operation decision accord with the operation principle commendably. So far, it has already achieved a very extensive application in the actual reservoir operation.

In the drawing and application of single reservoir operation chart, we take the water level as the operation indicator which can fully reflect the current energy state of single reservoir. In the joint operation of cascade reservoirs [31], in order to improve the utilization efficiency of water resources, we usually take the cascade system as a whole to consider, and we need to determine the cascade system's total output according to the beginning energy state of current stage. However, the same amount of water has different energy in different reservoirs because of the geographical position. Therefore, we cannot take the single water level as the operation indicator in the drawing and application of cascade reservoirs joint operation chart. Instead, we need a comprehensive indicator that can represent the overall energy state of cascade system very well. This comprehensive indicator is the total energy storage of cascade system, which can be calculated by formula (9), and the corresponding cascade reservoirs joint operation chart obtained through this indicator is the CRESOC.

Many scholars studied the CRESOC around the world [11,13], but the researches those had been done were mostly concentrated on the production by various optimization algorithms [20], such as the Linear Programming [19,28], Dynamic Programming [9,26,30,32],

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Bayesian Network [24], Genetic Algorithm(GA) [1,25], Particle Swarm Optimization (PSO) [2,37] and Progressive Optimality Algorithm (POA) [6,21]. Much less achievements about the conventional CRESOC were obtained, including the aspects of theory and application. Although it is simple and easy to get the cascade reservoirs joint operation chart by optimization algorithms, these methods are usually insufficient in terms of physical significance, and the credibility of the optimization results is also not high enough. On the contrary, the conventional reservoir operation chart is usually obtained through a reverse calculation using the hydrological data of typical years, and it has a clear physical meaning and highly reliability.

Different from the single reservoir operation with simple variable and independent operation unit [15], the acquisition of CRESOC is much more difficult and complicated than single reservoir operation chart. In this paper, we will draw the conventional CRESOC by combining with DCM. In the drawing procedure, in order to make the hydropower resources of cascade reservoirs get full utilization, there are several key technologies which can guarantee the correctness and rationality of CRESOC need to be analyzed and studied in detail.

The following parts of this paper are organized as follows. Section 2 presents a detailed derivation of DCM. Section 3 presents the drawing model of CRESOC based DCM, including the constraints in drawing CRESOC, the specific drawing process and the detailed steps in actual application. Section 4 shows the three key technologies in drawing CRESOC and the one key technology in the application of CRESOC. Section 5 will show the case study of Li Xiangjiang cascade reservoirs in southwest China, and in Section 5.2, the results will be presented and analyzed. Finally, the conclusions of this study will be provided in Section 6.

2. Discriminant criterion method

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 [8,18,27,35]. DCM is a relatively matured method in guiding cascade reservoirs joint operation at present [33], and its basic principle in guiding cascade reservoirs joint operation is to determine the optimal order of water storage and water supply for cascade reservoirs, so that to maximize the power generation and minimize the energy loss as far as possible. Compared with the other conventional operation methods, DCM can greatly increase the reliability of power generation and improve the benefits of water resource utilization. The detailed derivation of DCM can be described as follows.

In order to determine the order of storing or supplying water of each reservoir in cascade system, we can first take the average inflow rate of current stage as the actual inflow rate, and then calculate the total output of cascade system by this inflow rate when all reservoirs are assumed not to store or supply water. Assume the calculated total output is N_t, and the required total output of cascade system is N_t in current stage. When $N_t > N_q$ happens, the cascade system needs to store water. When $N_t < N_q$ happens, the cascade system needs to supply water. When $N_t = N_q$ happens, there is no water storage or supply. When the cascade system needs to supply water, the total quantity of supplied water is determined by the output increment, i.e., $N_g = N_q\text{-}N_t$. When the cascade system needs to store water, the total quantity of stored water is determined by the output decrement, i.e., $N_x = N_t\text{-}N_q$.

Assume that ΔE_g is the energy provided by the supplied water and it is provided by the jth reservoir, then, it can be expressed as: $\Delta E_g = 0.00272 \cdot \eta \cdot F_j \cdot DH_j \cdot \sum H_j$. Where DH_j is the water head decrement of the jth hydropower station because of ΔE_g. There are two parts of the extra energy loss caused by DH_j. The first part is the extra hydropower loss ΔE_W of the jth reservoir in generating hydroelectric power by the amount of water W_j in current stage, it can be expressed as $\Delta E_W = 0.00272 \cdot \eta \cdot W_j \cdot DH_j/2$. The other part is the extra energy decrement ΔE_V of the upstream reservoirs' available storage water $\sum V$ to the jth reservoir, it can be expressed as $\Delta E_V = 0.00272 \cdot \eta \cdot \sum V \cdot DH_j$. The sum of the extra energy loss is $0.00272 \cdot \eta \cdot (0.5W_j + \sum V) \cdot DH_j$. Therefore, because of the storage water consumption of the jth hydropower station, the extra energy loss of unit electricity generation in this stage is

$$K_j = (\Delta E_W + \Delta E_V)/\Delta E_g = \left(0.5W_j + \sum V\right) \Big/ \left(F_j \cdot \sum H_j\right) \tag{1}$$

In general, the calculated value of K is different when the water is supplied by different reservoir. For generating the electrical energy ΔE_g, the most favorable reservoir for supplying water is the one that can minimize the energy loss caused by generating unit electrical energy or maximize the total residual energy storage at the end of stage. That is to say, it is best that a hydropower station with the minimum K value to supply water first. When the reservoirs are parallel, the situation is similar, but the value of $\sum V$ is zero in formula (1), and the $\sum H_j$ turn into H_j. The units of ΔE, DH, F, $\sum H_j$, W, and $\sum V$ are kW·h, m, m^2, m, and m^3, respectively.

Assume that ΔE_x is the energy stored by the ith reservoir. Then, it can be expressed as $\Delta E_x = 0.00272 \cdot \eta \cdot F_i \cdot DH_i \cdot \sum H_i$. There are two parts of the extra energy obtainment caused by the water head increment DH_i. The first part is the extra energy obtainment ΔE_W of the ith reservoir in generating hydroelectric power by the amount of water W_i in current stage, it can be expressed as $\Delta E_W = 0.00272 \cdot \eta \cdot W_i \cdot DH_i/2$. The other part is the extra energy obtainment ΔE_V of the upstream reservoirs' available storage water $\sum V$ to the ith reservoir, it can be expressed as $\Delta E_V = 0.00272 \cdot \eta \cdot \sum V \cdot DH_i$. The sum of the extra energy obtainment is $0.00272 \cdot \eta \cdot (0.5W_i + \sum V) \cdot DH_i$. Therefore, at the end of this stage, the extra energy obtainment of cascade system to unit stored energy of the ith hydropower station is

$$K_i = (\Delta E_W + \Delta E_V)/\Delta E_x = \left(0.5W_i + \sum V\right) \Big/ \left(F_i \cdot \sum H_i\right) \tag{2}$$

In general, the calculated value of K is different when the water is stored by different reservoir. For storing the energy ΔE_x, the most favorable reservoir for storing water is the one that can maximize the extra energy increment caused by storing unit energy or maximize the total residual energy storage at the end of the stage. That is to say, it is best that a hydropower station with the maximum K value to store water first. When the reservoirs are parallel, the situation is similar, but the value of $\sum V$ is zero in formula (2), and the $\sum H_i$ turn into H_i. Comparing formula (1) and formula (2), it can be seen that the form of the two formulas are identical:

$$K = \left(0.5W + \sum V\right) \Big/ \left(F \cdot \sum H\right) \tag{3}$$

Formula (3) is called discriminant coefficient or discriminant criterion, and the way of using discriminant coefficient to guide the cascade reservoirs joint operation is called discriminant coefficient method.

3. DCM based drawing model of CRESOC

DCM has a clear physical meaning in cascade reservoirs joint operation, and many scholars all over the world have already received different degrees of success in cascade reservoirs joint operation by this method. However, it is found that there are also some inevitable defects of this method in guiding the actual