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Long-term Navigation Optimal Operation of Cascaded Reservoirs

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ABSTRACT: Long-term navigation optimal operation of cascaded reservoirs aims at determining optimal operation scheme of cascaded reservoirs to achieve maximum guarantee rate of navigation stage for 1 year while meeting all kinds of hydraulic and electric system constraints. This paper intends to present a novel optimal approach based on dynamic clustering method for the optimizing navigation problem. Due to different channel width and depth, which are determined by hydraulic condition, corresponding to different navigable stage for the ship, dynamic clustering method is employed to distinguish different operating patterns with different navigation condition. Based on the results of the navigation capacity recognition, operation scheme of cascaded reservoirs is continuously adjusted to obtain the maximum navigation probability of insurance through the solving method, artificial immune system. The proposed approach is applied to cascaded reservoirs in the lower Jinsha River. The simulation results obtained are feasible and very close to the optimal one, which shows that it has advantages in dealing with this navigation optimal problem.

Keywords: Long-term, Navigation optimal operation, Dynamic clustering method, Artificial immune system, Cascaded reservoirs

1 INTRODUCTION

With the development and utilization of basin water resources, a growing number of cascaded hydropower stations were built. In order to make full use of water resources, more and more studies focus on optimal scheduling of cascaded reservoirs. Establishment of cascaded reservoirs greatly improved hydraulic conditions of navigation channel. However, in the dry season, the backwater zone of reservoir restores to its natural state with low water level that is not navigable. Therefore, navigation optimal operation of cascaded reservoirs is employed to improve the hydraulic condition which can enhance the guarantee rate of navigation. Since the flood control and power generation is the main task of reservoir usually (Ahmadi, M., Haddad, O.B., et al 2014; Arunkumar, R., Jothiprakash, V., 2013.), few literatures focus on the long-term navigation operation. In recent decades, the navigation objective is considered as constraints by some scholars (Ackermann, T., Loucks, D. P., et al.2000; Wang, J., Zhang, Y., 2012), and is discussed often in short-term reservoir operation. However, long-term navigation operation is an important way to enhance the benefit of water resources especially for the cascaded reservoirs with shipping task, which are not taken into account reasonably in the aforementioned studies.

The purpose of long-term navigation optimal operation of cascaded reservoirs is to find out the maximize guarantee rate of navigation stage for a year while meeting all kinds of hydraulic constraints, such as water dynamic balance, generation limits, flood control limits, water release limits and reservoirs storage volume limits. The long-term navigation optimal operation of cascaded reservoirs plays an important role in comprehensive utilization of water resources. Many different methods have been used to solve optimal scheduling of cascaded reservoirs. Some of these methods are mixed-integer linear programming, nonlinear programming, and dynamic programming. All these algorithms have been successfully employed under certain practical constraints for some problems. As the development of computer technology, a lot of modern heuristics algorithms like genetic algorithm, particle swarm optimization, differential evolution and other artificial intelligent methods, have been presented for this scheduling optimization problem. In terms of the traditional algorithms, there need much more improvement when the problem size is large and complex. For these above artificial intelligent methods, they do not depend on the mathematic model, and have better ability to handle large-scale, nonlinear and non-convex problems compared to traditional methods. But these methods have more or less drawbacks, such as premature convergence and trap into local optimum, owing to their disadvantages of balancing global exploration and local exploitation. In recent years, a new optimization method known as Artificial Immune System has been applied for many optimization problems. This method is presented in 1990s(J.E. Hunt,1996; de Castro L.N,1999), which is a complex natural defense mechanism, and inspired by immunology, immune function and principles observed in nature. It has good robust, convergence properties.

However, the flow condition of channel is calculated by hydrodynamic model, which will cost much more time especial for long river in a long time period. Usually, we need to calculate the flow condition after each iterative calculation in modern heuristics algorithm. Therefore, as the number of variables and the number of iterations increases, the computation time dramatically increase, too. There are some approaches like artificial neural network and dynamic clustering method(), which can simulate the calculation procedure with less computation time. If the calculation procedure is replace by the artificial neural network or dynamic clustering method, the computation time can save much time for calculating flow condition. Thus, the dynamic clustering method is employed to distinguish different operating patterns with different navigation condition. Based on the results of the navigation capacity recognition, operation scheme of cascaded reservoirs is continuously adjusted to obtain guarantee rate of navigation stage through the solving method, artificial immune system.

In this paper, we present a novel optimal approach based on dynamic clustering method and artificial immune system for the optimizing navigation problem. The actual size, hydraulic relations of cascaded hydro systems, and the continuous reservoirs dynamic and constraints are considered. To show the validity of the proposed method, a case study based on a cascaded hydro system in lower Jinsha River is presented. And the efficiency and quality are discussed by comparing with other methods.

2 PROBLEM FORMULATIONS

2.1 *Objective function*

The objective of the problem is to maximize guarantee rate of navigation stage subjected to the operating constraints of a power system with a defined interval (usually 1 month or 10 days). Therefore, it can be formulated mathematically as the maximization of an objective function with constraints.

$$P_g = \max\frac{T_i}{T}\cdot\% = \max\frac{f(q_{i-1}, Z_i)}{T}\cdot\% \tag{1}$$

where P_g is the guarantee rate of navigation stage; T_i is the number of navigable days in one year, which don not consider the influence of weather and gate faults, and it depends on the $q_{i\text{-}1}$ and z_i; i the number of the reservoir; q is the discharge flow of reservoir; Z_i is the water level of reservoir.

2.2 *Constraints*

Due to most reservoirs are multi-purpose water control project, the optimal scheduling of hydro system should subject to the following constraints:

(1) Water dynamic balance

$$V_{i,t+1} = V_{i,t} + \left[I_{i,t} - q_{i,t} - S_{i,t} + \sum_{k-1}^{N_{ui}}\left(q_{k,t-T_{ki}} + S_{k,t-T_{ki}}\right)\right]\Delta t \tag{2}$$

where $I_{i,t}$, $S_{i,t}$ are the inflow and spillage of the *i*th reservoir at the *t*th period, N_{ui} is the number of upstream plants directly above the *i*th hydro unit, and T_{ki} is the water transport delay between reservoirs *k* and *i*.

(2) Hydro power limits:

$$P_{i,t}^{\min} \le P_{i,t} \le P_{i,t}^{\max} \tag{3}$$

where $P_{i,t}^{\min}$ and $P_{i,t}^{\max}$ are the minimum and maximum power generation of *i*th hydro plant at *t*th period, respectively.

(3) Water discharge limits

$$q_{i,t}^{\min} \le q_{i,t} \le q_{i,t}^{\max} \tag{4}$$

where $q_{i,t}^{\min}$ and $q_{i,t}^{\max}$ are the lower and upper water discharge limits of the *i*th reservoir at *t*th period for navigation.

(4) Reservoir storage volume limits

$$V_{i,t}^{\min} \le V_{i,t} \le V_{i,t}^{\max} \tag{5}$$

where $V_{i,t}^{\min}$ and $V_{i,t}^{\max}$ are the minimum and maximum storage volume of the *i*th hydro unit at *t*th period, respectively.

(5) Water head limits

$$h_{i,t}^{\min} \le h_{i,t} \le h_{i,t}^{\max} \tag{6}$$

where $h_{i,t}^{\min}$ and $h_{i,t}^{\max}$ are the allowable upper and lower net water head limits of *i*th hydro station at *t*th period.

(6) Initial and terminal reservoir storage volumes limits

$$V_{i,0} = V_i^{Begin}, \quad V_{i,T-1} = V_i^{End}, \quad \mathrm{i} = 1, 2, \ldots, N \tag{7}$$

where V_i^{Begin} and V_i^{End} are the initial and terminal reservoir storage limits of *i*th reservoir.

(7) Daily variation in water level limits

$$\Delta Z_i^d \le \Delta Z_{d,\max} \tag{8}$$

where ΔZ_i^d is the daily variation in water level and $\Delta Z_{d,\max}$ is the maximum daily variation in water level limits.

3 SOLUTION TECHNIQUES

The optimal scheduling of the cascade reservoirs combined with shipping can be summarized into a nesting optimization mode between water regulation of a cascade reservoirs and hydrodynamic simulation. At first, give a scheduling objective, then take the water level from the water regulation plan and discharged volume during operation as the input condition of the simulation of the channel flow and use improved AIS to solve alternately. In this process, the key problem is how to deal with hydrodynamic simulation effectively and obtain a best solution in a short time. Here, dynamic clustering method and improved AIS is used for handle this problem.

3.1 *Dynamic clustering method for hydrodynamic simulation*

To study the fluctuation of the channel flow of the reservoirs, we use one-dimensional hydrodynamic model to simulate the river channel. The formulations are described as follows.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_s \tag{9}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(P_c+\frac{Q^2}{A}\right)=gA\left(S_0-S_f\right)+F \tag{10}$$

where A is discharge cross-sectional area; Q is water flow of area; q_s is distributary flow; P_c is hydrostatic pressure of discharge cross-sectional; F is the acting force along the x axis direction projection; S_0 is the river bed slope; $s_f = n^2 Q|Q| / A^2 R^{3/4}$, R is hydraulic radius, and n is roughness coefficient.

In the process of optimization, the computation of hydrodynamic simulation for the channel in cascaded reservoirs needs much more computation time. In order to deal with this problem, dynamic clustering method is used to classify hydrodynamic numerical simulation samples of the channel in reservoir areas by classifying and combining different water quantity and water level generally. Then, different water and combination modes of flow condition in the reservoir area channel. Based on the classification, guarantee rate of navigation stage for 1 year can be calculated in a short time. The core of dynamic clustering method included the following contents:

- Select the proper distance that can be used to measure the similarity of samples;
- Give the criterion function that can evaluate the quality of clustering results;
- Obtain the best clustering results by a certain iterative algorithm.

In the dynamic clustering method, the least sum of square error is employed as the criterion function, which is described as follows:

$$J_e=\sum_{i=1}^{c}\sum_{y\in\Omega_i}\left\|y-m_i\right\|^2 \tag{11}$$

where $m_i=\frac{1}{N_i}\sum_{y\in\Omega_i} y$, and m_i is average value of the ith area cluster name Ω includes the number of N samples; y is one of the samples; c is the number of clusters; J_e is the evaluation result.

3.2 *Improved artificial immune system method*

Artificial immune system (AIS) mimics the biological immune system of vertebrates, which has the principles of clone generation, proliferation and maturation. Previous work has been done on the uses of AIS for many optimization problems (Basu M, 2011; Timmis J,2000) The clonal selection describes how the adaptive immune system reacts to antigen. Here, the AIS has two population of B cells and T cells. Each B cell object can describes as a data item that is being used for learning and responding to a stimulus closely matching item. The main stimulus is the affinity between the B cell and the pathogen by calculating the affinity by the objective function (1). First, a random solutions are generated as antibodies. And then through proliferation and maturation operation, its capability of recognize specific antigen have been improved. The proliferation of antibodies is implemented by cloning the each antibody depending on the affinity by the equation. Next, the antigenic affinities of the antibodies are mutated by the equation (12). By this operation, the population of antibodies can keep the diversity to avoid the premature convergence. Additional, all kinds of constraints need to be handle by their features. In this paper, we add archives set for AIS, which can enhance the exploration ability during the evolution process.

$$q_g'=q_g+B\times\frac{F_k}{F_{\min}}\times Rand(0,1)\times(q_j^{\max}-q_j^{\min}) \tag{12}$$

where q_g is the decision variables, B is a scaling factor, F_k is the value of objective function and Rand(0,1) represents a random variable between 0 and 1.

Archive set in this paper is used to preserve a certain better feasible solution found along the evolutionary process. After the clonal proliferation and mutation operation for the population, some number of the best individuals of archive set will be selected as the initial population. Therefore, the best feasible solution of the present generation can improve other mutated clone with better ability to recognize antigens.

Compared with the schedule period of long-term optimal operation which is usually a month, the water transport delay is much shorter. As a result, it can be negligible for simplification in the practical calculation. Spillage occurs only when the water discharge of the station exceeds its maximum discharge limit and the storage exceeds the maximum allowed storage of the reservoir. The main process of the improved artificial immune system with external archives for solving cascaded hydro system scheduling problem can be summarized as follows:

- Step 1: Initialize population of IAISEA, then the antibodies and affinity are taken as the decision variable and objective function respectively.
- Step 2: Handle power output limits, reservoir storage volume limits, water discharge limits, initial and terminal reservoir storage limits.
- Step 3: Evaluate the affinity of each antibody, and update the archive set which include the certain number of feasible solutions.
- Step 4: Implement the clonal proliferation and mutation operation for the population.
- Step 5: Evaluate affinity of the mutated clone, save the best feasible solution to the archive set and eliminate the poor solution in the archive set.
- Step 6: Select quarter size of archive set as the initial population from the antibodies and mutated clones.
- Step 7: If the maximum number of generation is reached, the best solution in the archive set is output and terminate this process; otherwise, go back to Step 2.

4 CASE STUDY

The cascaded hydro system in lower Jinsha River includes four reservoirs: Wudongde (WDD), Baihetan (BHT), Xiluodu (XLD) and Xiangjiaba (XJB). This cascaded reservoir will be constructed and put into operation in 2020. In this paper, it is employed to verify the feasibility and efficiency. The entire scheduling period is 1 year which includes 365 days. The hydraulic relationship, hydropower station power generation coefficients, reservoir limits, power output limits are given in the table 1. One of the history inflow data was used to test for this case study.

Table 1. Parameters of cascaded hydro system in Jinsha River

Reser-voirs	max $V(10^8m^3)$	min $V(10^8m^3)$	maxq (m^3/s)	min $q(m^3/s)$	max Z(m)	min Z(m)	max p(10MW)	min p(10MW)
WDD	58.96	44.75	49800	1830	975	950	870	0
BHT	179.24	123.01	43700	1300	820	760	1305	0
XLD	117.35	73.38	49700	1500	600	540	1386	0
XXB	49.76	40.73	48400	1500	380	370	640	0

The proposed dynamic clustering method and improved AIS were implemented 30 times from different initial populations and the best result was selected as the final optimal result. The initial value of water level for the cascaded reservoirs is the maximum water level. The tolerance value of equally constraint of water balance is $500m^3$. Fig.1 shows the variation trend of the guarantee rate of navigation stage with the number of iterations increased. From this fig, it is easy to see that the value of the guarantee rate is stable when the iterations reached 168, which means the proposed approach can obtain the best result with little iteration.

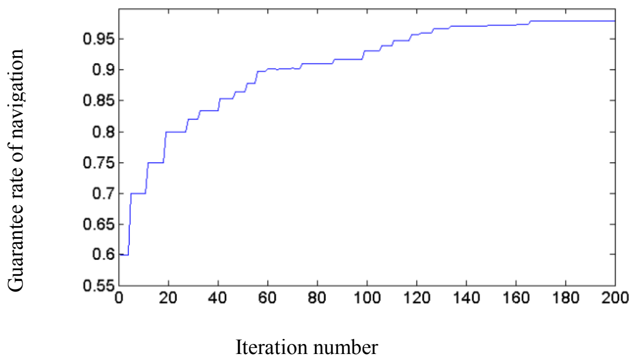

Figure1. Variation trend of the guarantee rate of navigation stage with the number of iterations increased.

Table.2 demonstrates the results of navigation and guarantee rate of navigation for the cascaded reservoir in the lower of Jinsha River. From Table.2 we can see that the navigation mileage is increased by the optimal operation of cascaded reservoir compared to the normal operation of cascaded reservoir. And the guarantee rate of navigation is also increased to 98.3% (average of four reservoirs). All these results indicate that the proposed approach is feasibility and efficiency.

Table 2. Comparison results of before optimization and after optimization

Reservoirs	**Navigation mileage（km）**		**Guarantee rate of navigation（%）**	
	Before optimization	after optimization	Before optimization	after optimization
WDD	197.0	197.0	93.5	98.1
BHT	179.2	186	92.4	98.4
XLD	196.7	196.7	93.6	98.8
XJB	152.8	154.5	95.7	97.9

5 CONCLUSIONS

In this paper, long-term navigation optimal operation of cascaded reservoirs in lower Jinsha River was studied. The dynamic clustering method is used to classify the hydrodynamic simulation samples for the channel of cascaded reservoir to reduce the dimension of hydrodynamic simulation. Meanwhile, an improved artificial immune system with external archive set is proposed to solve this optimization problem. From the case study, we can see that the navigation of cascaded reservoir can be improved by the proposed approach. It is easy to see that the guarantee rate of navigation is increased to 98.3% (average of four reservoirs), which shows the proposed method has good feasibility and effectiveness, and demonstrates the presented method can deal with this optimization problem with high dimensions.

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