臺灣水利　第 65 卷　第 1 期
民國 106 年 3 月出版

Taiwan Water Conservancy
Vol. 65, No. 1, March 2017

Multi-objective Optimization of Cascaded Hydropower Station Groups Based on Bat Algorithm

基於蝙蝠演算法的梯級水電站群多目標優化

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ABSTRACT

Hydropower is an important, clean and renewable energy. Under rapid development of clean and low-carbon economy, studying how to realize the dispatching and operation of giant-scale cascaded hydropower station groups is of great significance. With the advancement of the hydropower development, the number of hydropower stations continuously increases on one river. The traditional optimization algorithms, such as dynamic programming (DP) algorithm and progressive optimization algorithm (POA), encounter dimension disasters and often take a long time for computation. Due to these shortcomings, it would be rather difficult for these algorithms to meet the requirements for optimizing algorithms with the increasing number of hydropower stations on a river. For this purpose, this study introduces the bat algorithm (BA), which can dynamically control the mutual conversions of local and global search and therefore avoids local optimal solutions and achieves better global convergence, to realize the multi-objective optimization model of cascaded hydropower station groups. Moreover, the BA is applied to the multi-objective optimization of cascaded hydropower stations, Xiluodu hydropower station and Xiangjiaba hydropower station, on the lower reaches of Chin-sha River, China. By comparing the application results with the improved partheno genetic algorithm (IPGA), real-code genetic algorithm (RCGA) and progressive optimization algorithm (POA), it shows that efficiency and accuracy are BA's two prominent strengths.

Keywords: Bat algorithm, Cascaded hydropower station group, Multi-objective optimization.

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摘　　要

由於水電是重要的清潔可再生能源，在清潔低碳發展的背景下，研究實現巨型梯級水電站群聯合運行的方法具有重要的理論和現實意義。隨著水電開發的不斷推進，水電系統的規模越來越複雜、電站數量逐漸增加，傳統的動態規劃演算法和逐步優化演算法等面臨著“維數災”和計算時間過長等困難，難以滿足梯級水電站聯合調度模型求解的需求。為此，本文引入能夠實現局部搜索和全域搜索動態切換的蝙蝠演算法(Bat Algorithm, BA)進行梯級群的多目標優化，並以金沙江下游溪洛渡、向家壩梯級為例驗證演算法的可行性和有效性。通過與遺傳演算法、改進單親遺傳演算法、逐步優化演算法比較分析，結果表明：蝙蝠演算法能夠有效避免局部最優解，具有更好的全域收斂性，在求解效率和準確度上具有明顯的優越性。

關鍵詞：蝙蝠演算法，梯級水電站群，多目標優化。

1. Introduction

Hydropower as a clean and renewable energy with feature such as technologies fully developed, giant development scales, low running costs and rapid load response capacities plays a very important role in China’s energy system (Ji *et al*., 2013). Currently, China is committed in developing green and low-carbon economy and naturally, forming giant-scale cascaded hydropower stations. In such context, developing approach to realize multi-objective optimization of giant-scale cascaded hydropower station groups and maximize the comprehensive utilization benefits of electricity generation, flood control, shipping, irrigation and ecology of cascaded hydropower station groups is of theoretical and practical significance.

As cascaded hydropower stations on a river show hydraulic and electric contacts with complex optimization variables and constraints, the multi-objective optimization of cascaded hydropower station groups is a large-scaled, dynamic, nonlinear and systematical optimization problem (Wang *et al*., 2015; Feng *et al*., 2014; Ming *et al*., 2015; Feng *et al*., 2015). The core of this problem is how to establish a scientific and reasonable optimal operation model and choose suitable solutions to the model (Chen *et al*., 2008). At present, the commonly used methods of optimal operation of hydropower stations mainly include dynamic programming (DP) (Labadie, 2004; Yeh, 1985; Kumar and Baliarsingh, 2003), progressive optimization algorithm (POA) (Howson and Sancho, 1975; Lucas and Perera 1985; Nanda *et al*., 1986; Turgeon, 1981), genetic algorithm (GA) (Chen, 2003; Deb, 1999; Hincal *et al*., 2011; Holland, 1975; Chen *et al*., 2010; Zheng *et al*., 2013), particle swarm optimization (PSO) (Saber 2012; Wu *et al*., 2008; Zhang *et al*., 2007; Peng *et al*., 2009) and so on. As for the solutions to multi-objective optimization problems of hydropower station groups, DP encounters dimension disasters and the computation time is unfavorably long (Christiano and Luiz, 1995). GA has significant advantages for complex object functions, but demonstrates obvious deficiency in the treatment and convergence speed of multi-constraints (Li and Tong, 1999; Li *et al*., 2004; Zhu and Duan, 2008). In addition, although PSO has a few merits such as simple implementation, few parameters and fast convergence, it tends to be trapped in local optimization (Li *et al*., 2006), which renders high accuracy less reachable. With the increase of the numbers of hydropower stations, POA occupies more and more computer memories, taking more time for computation and runs at a low speed (Cheng *et al*., 2012; Zhang *et al*., 2004).

Bat algorithm (BA) is a meta-heuristic intelligent algorithm proposed in recent years based on the echolocation behaviour of bats (Yang, 2010). BA increases the diversity of solutions in the population by the frequency tuning technology. Meanwhile, it uses the automatic zooming to try to balance exploration and exploitation during the search process by mimicking the variations of pulse emission rates and loudness of bats when searching for preys (Yang and He, 2013). Preliminary studies show that it is very promising and outperforms existing algorithms such as GA and PSO as well as Harmony Search (Yang, 2011). The primary reason is that BA combines major advantages of existing algorithms. Moreover, PSO and harmony search are the special cases of the BA under appropriate simplifications (Yang and Hossein, 2012). Since BA has been developed, it has been studied by many scholars across the world and has been applied in many fields such as optimization, classifications, image processing, feature selection, data mining and so on (Li *et al*., 2013; Liu and Ye, 2013). The results reveal that compared with intelligent algorithms consisting of GA, artificial neural network (ANN) algorithm and other commonly used methods, BA algorithm can dynamically control the mutual conversions of local and global search and therefore avoid local optimal solutions and achieve better global convergence.

Preliminary studies suggested that BA is very promising for solving nonlinear global optimization problems (Yang, 2010). Furthermore, BA has also been applied to solve multi-objective optimization problems (Yang, 2011), while the results suggested positive efficiency (Yang and Hossein, 2012). By introducing the BA to solve multi-objective optimization models of cascaded hydropower station groups, this study attempts to provide a new solution. Furthermore, this study takes the multi-objective optimization of Xiluodu hydropower station and Xiangjiaba hydropower station on the lower reaches of Chin-sha River as examples. By comparing and analyzing calculation results of BA with those of the improved parallel genetic algorithm (IPGA) proposed by Wang *et al*. (2015) and commonly used real-code genetic algorithm (RCGA) and POA, the effectiveness and feasibility of BA are verified.

2. Bat behaviour and BA

2.1 Echolocation of bats

Bats are fascinating animals. They are the only mammals with wings and they also have advanced echolocation capability, which enables them to detect prey, avoid obstacles, and locate their roosting crevices in the dark. These bats emit a very loud sound pulse and listen for the echo that bounces back from the surrounding objects. Their pulses vary in properties, which is a result from the difference in species, and thus, the difference in hunting strategies deployed. Most bats use short, frequency-modulated signals to sweep through about an octave, and each pulse lasts a few thousandths of a second (up to about 8 to 10 ms) in the frequency range of 25 kHz to 150 kHz. In order to accurately and quickly find prey, bats emit loud ultrasonic pulses with low emission rates, to narrow search ranges using the specific ability of echolocation. Moreover, the ultrasonic pulses become quieter gradually as they fly towards the prey, and the ultrasonic pulses even become silent when they are very close to prey, while the rates of pulse emission raise quickly, so as to search and capture prey easily.

Studies show that bats use the time delay between emission and detection of the echo, the time difference between their two ears, and the loudness variations of the echoes to sense three-dimensional surroundings. They can detect the distance and orientation of the target, the type of prey, and even the moving speed of the prey such as small insects. Indeed, studies suggested that bats seem to be able to distinguish targets by the variations of the Doppler Effect induced by the wing-flutter rates of the target insects. Obviously, some bats have good eyesight, and most likely, good olfaction as well. In reality, they will use all the senses in combination to maximize the efficiency of prey detection and the smoothness in navigation. The BA mainly uses some features of the echolocation which may link with the objective function of an optimization problem.

2.2 BA

BA is an intelligent algorithm for solving optimization problems by simulating the echolocation ability of bats. When abstracting the echolocation behaviors of bats as the process of mathematical modeling, it is assumed that bats in a population abide by the following three idealized rules:

(1) All bats use echolocation to sense distance and orientation, and they distinguish prey and background barriers by some particular methods;

(2) Bats fly randomly with velocity v_i at position x_i with a fixed frequency range $[f_{\min}, f_{\max}]$, varying wavelength λ and loudness A to search for prey, they can automatically adjust the frequency of their emitted pulses and adjust the pulse emission rate $r \in [0, 1]$, depending on the proximity of their target;

(3) Although the loudness can vary in many ways, we assume that it varies from a large (positive) A_0 to a minimum constant value $A_{\min}$.

2.2.1 Bat motion

BA is a bionic optimization algorithm established on the basis of populations. In the algorithm, each bat is a basic unit and its position represents a group of feasible solutions to optimization problems. The desirableness of the position, which denotes the satisfaction of the solutions, is judged by the values of fitness functions. Moreover, the process of finding the optimal solutions is the process that bat groups constantly update their own positions with the optimal bat. The position and velocity of bats are updated according to the following formulas:

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \tag{1}$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_*) f_i \tag{2}$$

$$x_i^t = x_i^{t-1} + v_i^t \tag{3}$$

Where f_i represents the frequency of ultrasonic pulses emitted by the ith bat, while $f_{\min}$ and $f_{\max}$ denote the minimum and maximum values of the frequency, respectively. $\beta \in [0, 1]$ is a random vector drawn from a uniform distribution. Furthermore, v_i^t represents the velocity of the ith bat in the tth iteration process, while x_i^t indicates the position of the ith bat in the tth iteration process, which denotes the parameter to be calculated in specific optimization problems. Here x_* stands for the current global best position which is located after comparing all the positions among all the n bats at each iteration t.

Initially, each bat is randomly assigned a frequency which is drawn uniformly from $[f_{\min}, f_{\max}]$. For this reason, bat algorithm can be considered as a frequency-tuning algorithm to provide a balanced combination of exploration and exploitation. The loudness and pulse emission rates essentially provide a mechanism for automatic control and auto zooming into the region with promising solutions.

Meanwhile, BA has the local search ability. When certain conditions are satisfied, that is, a random number within [0, 1] is generated to compare with the pulse emission rate of current bats and the random number is larger than the pulse emission rate, bats begin local search and the updated formula is:

$$x_{new} = x_{old} + \theta A^t \tag{4}$$

Where x_{new} and x_{old} respectively represent the new position and the position randomly selected from the current position set. In addition, $\theta \in [-1, 1]$ is a random number drawn from a uniform distribution, and $A^t = \langle A_i^t \rangle$ is the average loudness of all the bats in the tth iteration process.

2.2.2 Variations of loudness and pulse emission

In order to provide an effective mechanism to control the exploration and exploitation and switch to exploitation stage when necessary, the loudness A_i and the pulse emission rate r_i have to be updated accordingly as the iterations proceed. Since the loudness gradually decreases once a bat has found its prey, while the pulse emission rate increases, the loudness can be determined at any value of convenience. For example, we can use $A_0 = 100$ and $A_{\min} = 1$. For simplicity, we can also use $A_0 = 1$ and $A_{\min} = 0$, assuming $A_{\min} = 0$ means that a bat has just found the prey and temporarily stop emitting any sound. With these assumptions, the updated formulas of loudness and pulse emission rate are shown as:

$$A_i^{t+1} = \alpha A_i^t \tag{5}$$

$$r_i^{t+1} = r_i^0 [1 - \exp(-\gamma t)] \tag{6}$$

Where A_i^t denotes the loudness of the ith bat in tth iteration process. α, as attenuation coefficient of loudness, is a constant whose range of value is $0 < \alpha < 1$. r_i^{t+1} and r_i^0 represent the pulse emission rate of the ith bat in the $(t+1)$th iteration process and the largest pulse emission rate of the ith bat (generally being 1), respectively. γ, as an increase coefficient of pulse emission rate, is a constant whose value is greater than 0, represented by $\gamma > 0$. In practice, we generally use $\alpha = \gamma$ which varies within the range of [0.90, 0.98] in most simulations (Yang and He, 2013).

2.2.3 Parameter settings

The characteristic parameters of BA consist of the population number n, loudness A, pulse emission rate r and frequency f.

(1) Population number (n). In theory, the larger the population number is, the stronger the search ability of the algorithm and the higher the convergence precision are. However, with the increase of population number, the calculation amount enlarges and therefore the convergence speed decreases. In practice, the value of n can be obtained according to the specific conditions. As for the general optimization problems, the value in the range of [15, 50] can meet the requirements (Yang, 2010).

(2) Loudness (A). Generally, the loudness of pulses emitted by bats can be calculated by Formula (5). Due to $0 < \alpha < 1$, the loudness reduces gradually with the increase of iteration times and is determined by the initial loudness A_i^0. In practical applications, the initial loudness A_i^0 is generally set within [1, 2] (Yang, 2010).

(3) Pulse emission rate (r). Each ultrasonic pulses emitted by bats may last typically 5-20 ms, and bats emit about 10-20 such sound bursts per second. When hunting for prey, the pulse emission rate can be sped up to about 200 pulses per second when they fly near their prey. The pulse emission rate r is generally obtained according to Formula (6) and valued in the range of [0, 1]. $r = 0$ indicates that no sound waves are emitted, while $r = 1$ denotes the maximum pulse emission rate.

(4) Frequency (f). When bats emit ultrasonic pulses to detect prey, they generally emit a group of pulses with different frequencies. In general the frequency f is in the range of $[f_{\min}, f_{\max}]$ and corresponds to a range of wavelength $[\lambda_{\min}, \lambda_{\max}]$. Furthermore, the wavelength λ of echoes is determined by the size of detected objects. Therefore, the larger the frequency is, the shorter the wavelength and the narrower the range detected by ultrasonic pulses are. As for a specific optimization problem, the value range of frequency can be determined according to the value ranges of parameters to be calculated. During general optimization problems, we can use $f_{\min} = 0$ and $f_{\max} = 2$.

2.3 Solving process of BA

The specific steps of BA for solving optimization problems are as follows:

(1) Determining the objective function $f(x)$ (usually

is also the fitness function), where $x = (x_1, x_2, \ldots, x_d)^T$ and d is the dimension of the problems to be solved, and the initial characteristic parameters include the population number n, the maximum frequency $f_{\max}$, the minimum frequency $f_{\min}$, the initial loudness A_0, the attenuation coefficient α of loudness, the maximum pulse emission rate r_i^0 and the increase coefficient γ of pulse emission rate. At the same time, the requirements for calculation accuracy, the maximum iteration times and the relevant parameters of the problems to be optimized are given.

(2) Generating the initial population including the positions, flight velocities and pulse frequencies of bats randomly. Furthermore, the initial fitness of bats is calculated and the initial optimal solutions are determined.

(3) Global search. According to Formulas (2) and (3), the positions and velocities of all bats are updated to calculate the current fitness values.

(4) Local search. In accordance with Formula (4), the status of these bats which satisfy those conditions of local search is updated, so as to obtain new positions and then calculate the fitness after local update.

(5) Determining whether these solutions of local update can be accepted or not. By comparing the values of fitness function of bats before and after local update, these solutions of local update are accepted only if those related conditions are satisfied. Otherwise, these solutions are refused. In addition, according to Formulas (5) and (6), the loudness A_i and the pulse emission rate r_i are updated.

(6) Comparing the fitness values of all bats after updating with the historical global optimal value, and then determining the currently optimal solutions.

(7) Determining whether the stop condition is satisfied. If the condition is met then we have our final output here. Otherwise, the next iteration would initiate from step (3) until meet the stop condition.

The flow chart of the optimization process of Bat Algorithm is shown in Figure 1.

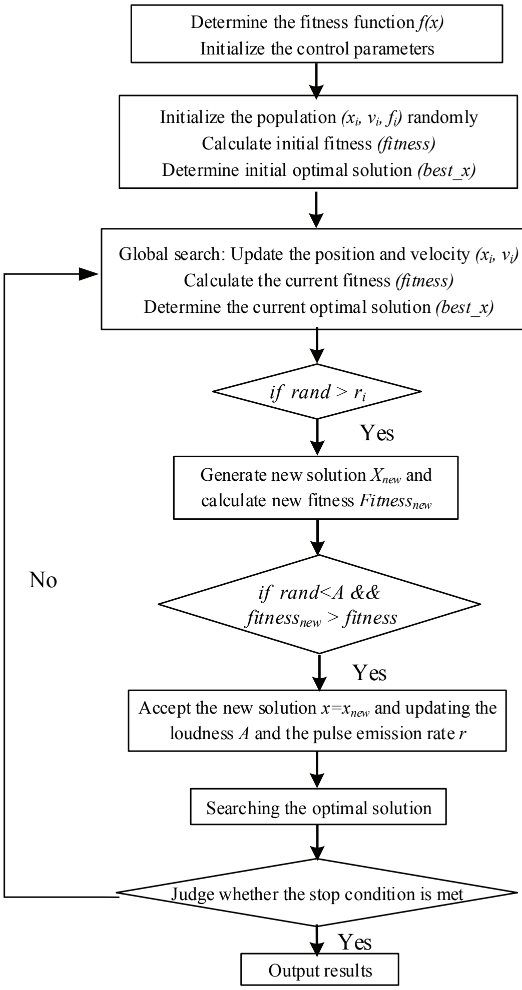

Fig. 1. Flow chart of BA.

3. The multi-objective optimization model

The multi-objective optimization model of cascaded hydropower station groups includes objective functions and constraints. The objective functions are determined according to these tasks of reservoirs such as power generation, flood control and irrigation. Most reservoirs are mainly used for generating electricity, simultaneously consider the requirements of flood control, irrigation, shipping and so on (Ma and Wang, 2003; Zhou *et al*., 2010).

In order to further achieve the higher standard of clean and low-carbon development and the peak shaving and frequency modulation of power grids, provide clean and renewable hydropower energy as much as possible and maximize uniform and reliable generated outputs, and ensure the power system to run safely and stably, this paper establishes the optimal dispatch model by employing the maximization of total electricity generation as the objective functions while maximizing the minimum generated output of the cascaded hydropower station groups. In the meantime, the other requirements are applied as constraints.

3.1 Objective functions

The maximization of total electricity generation as the objective functions while maximizing the minimum generated output of the cascaded hydropower stations is to maximize the annual energy production and the minimum generated output of these hydropower stations, under the condition that the comprehensive utilization requirements of flood control are met. The objective functions are expressed as:

The objective function *I*, maximize the total electricity generation:

$$E = \max \sum_{p=1}^{N} \sum_{k=1}^{T} (A_{p,k} \cdot Q_{p,k} \cdot H_{p,k} \cdot M_k) \quad (7)$$

The objective function *II*, maximize the minimum generated output:

$$NP = \max \min_{1 \le k \le T} \sum_{p=1}^{N} (A_{p,k} \cdot Q_{p,k} \cdot H_{p,k}) \quad (8)$$

Where, E, NP, p, and k represent the maximized annual electricity generation (MW•h), the maximized annual minimum generated output (MW), the serial number of a hydropower station and the calculation time interval number, respectively. $A_{p,k}$, $Q_{p,k}$ and $H_{p,k}$ indicate the generated output coefficient, the water discharge (m^3/s) and the net head (m) of the pth hydropower station in the kth time interval, respectively. In addition, M_k, N and T denote the electricity generation hours (h) in the kth time interval, the total number of cascaded hydropower stations and the total number of calculation time intervals in a year, respectively.

In the objective function I, the total electricity generation represents the sum of the electricity generation of cascaded hydropower stations. As for the objective function *II*, the minimum generated output represents the minimum value of the sum of the generated output of cascaded hydropower stations during each calculation time interval. For example, suppose that there are two cascaded hydropower stations in total (hydropower stations A and B). The total number of calculation time intervals is three (1^{st}, 2^{nd} and 3^{rd}), the generated outputs of hydropower station A during the three calculation time intervals are 120 MW, 80 MW and 90 MW, respectively, and those of hydropower station B during the three calculation time intervals are 100 MW, 90 MW and 90 MW, respectively, then the sums of the generated outputs of the cascaded hydropower stations during the three calculation time intervals are 220 MW, 170 MW and 180 MW, respectively, and the minimum value of the sum of the generated output of the cascaded hydropower stations during the three calculation time intervals, namely the minimum generated output, is 170 MW. By optimizing the operation mode of hydropower stations A and B, the generated output of the cascaded hydropower stations may become more uniform, then the minimum generated output may increase to 180 MW or even higher.

Obviously, this is a multi-objective optimization problem, which was usually handled with the weighted method and constraint method (Reddy and Kumar, 2006). For the constraint method, except the major objective, other objectives are constrained to specific values to yield a Pareto optimal solution. The model is run with a series of the specific values to find corresponding Pareto optimal solution until the trade-off relationship between the objectives is sufficiently represented. For the weighted method, all objectives are incorporated into comprehensive objective function with corresponding weights, and a different set of weights is adopted in each run of the optimization model for the optimal trade-off solution. However, the constraint method is used more often by various researchers when it comes to multi-objective optimization problem (Yeh and Becker, 1982; Liang *et al*., 1996). The reason for such difference is that the weighting method cannot identify its concavities and tend to leave out some part of the Pareto optimal solution set, if the non-inferior solution set is not convex. Furthermore, many combinations of weights may lead to the same Pareto optimal solution, which makes the weighting method time-consuming.

For the above-mentioned reasons, the constraint method is employed in this paper. When finding the solutions to the model, the objective function *II* is transferred into a constraint for the reliable generated output of a cascaded hydropower station group. Then, the authors attempt to meet this constraint and, at the same time, maximize the objective function *I*. If this constraint cannot be met completely, the objective function *I* is realized under the condition of this constraint being met as far as possible.

3.2 Constraints

(1) Balance constraint of water

$$V_{p,k+1} = V_{p,k} + (q_{p,k} - Q_{p,k} - S_{p,k})\Delta t \quad \forall k \in T \tag{9}$$

Where, $V_{p,k+1}$ represents the reservoir storage volume of the pth hydropower station at the beginning of the $(k+1)$th time interval, that is, the reservoir storage volume of the pth hydropower station at the end of the kth time interval, (m^3). Moreover, $q_{p,k}$, $Q_{p,k}$ and $S_{p,k}$ indicate the reservoir inflow (m^3/s), the water discharge (m^3/s) and the waste water (m^3/s) of the pth hydropower station in the kth time interval, respectively. Δt denotes the length of the calculation time interval, (s).

(2) Balance constraint of flow

$$q_{p+1,k} = Q_{p,k} + S_{p,k} + q_{p,k}' \quad \forall k \in T \tag{10}$$

Where, $q_{p+1,k}$ shows the reservoir inflow (m^3/s) of the $(p+1)$th hydropower station in kth time interval. $Q_{p,k}$ and $S_{p,k}$ represent the water discharge (m^3/s) and the waste water (m^3/s) of the pth hydropower station in the kth time interval, respectively. Furthermore, $q_{p,k}'$ indicates the local inflow from the pth reservoir to $(p+1)$th reservoir in the kth time interval (m^3/s).

(3) Water level constraint of reservoirs

$$Z_{p,k}^{\min} \le Z_{p,k} \le Z_{p,k}^{\max} \quad \forall k \in T \tag{11}$$

Where, $Z_{p,k}^{\min}$ and $Z_{p,k}$ represent the lowest required water level and the upriver water level of the pth reservoir in the kth time interval, (m), respectively. $Z_{p,k}^{\max}$ denotes the permissible highest level of pth hydropower station in the kth time interval, (m), which is generally determined considering the safety of reservoirs, such as the limitation for flood prevention during flood season.

(4) The water discharge constraint of reservoirs

$$Q_{p,k}^{\min} \le Q_{p,k} \le Q_{p,k}^{\max} \quad \forall k \in T \tag{12}$$

Where, $Q_{p,k}^{\min}$ represents the required minimum water discharges of the pth hydropower station in the kth time interval, (m^3/s), which is determined by comprehensive utility of hydropower station, such as the ecological water consumption of the downstream and the water consumption for electricity generation, irrigation and shipping. While $Q_{p,k}$ and $Q_{p,k}^{\max}$ denote the water discharge and the allowable maximum water discharge of the pth hydropower station in the kth time interval, (m^3/s), respectively. In general, the allowable maximum water discharges are determined according to the requirements of flood prevention in the downstream.

(5) The generated output constraint of power stations

$$N_{p,k}^{\min} \le N_{p,k} \le N_{p,k}^{\max} \quad \forall k \in T \tag{13}$$

Where, $N_{p,k}^{\min}$, $N_{p,k}$ and $N_{p,k}^{\max}$ indicate the allowable minimum generated output, allowable maximum generated output and actual generated output of the pth power station in the kth time interval, (MW), respectively.

(6) Nonnegative constraints

All the above variables are nonnegative constraints.

4. Implementation of BA for multi-objective optimization model

When the BA is used to solve the multi-objective optimization model of hydropower station groups, each bat represents an optimization strategy of cascaded hydropower stations. The spatial position of a bat denotes the water level of a hydropower station which was expected to be reached at the end of a calculation time interval. In addition, the moving speed of bats indicates the fluctuating speed of the water level of hydropower stations at the end of a calculation time interval, and the annual electricity generation of cascaded hydropower station groups as the values of fitness functions is used to judge the desirableness of the position of bats, which denotes the satisfaction of the solutions. The larger the annual electricity generation of cascaded hydropower station groups, the better the position of bats is. Through the global and local changes of the position of bats, BA searches the solutions for multi-objective optimization. Moreover, the optimal bats at the last iteration are the best optimization strategies of cascaded hydropower station groups. According to the basic theories of BA, the main steps for solving the multi-objective optimization model of hydropower station groups are shown as follows:

(1) Initializing the characteristic parameters of BA which mainly include the population number n of the bats, the minimum frequency $f_{\min}$, the maximum frequency $f_{\max}$, the attenuation coefficient α of loudness, the increase coefficient γ of pulses and the maximum iteration times *max_generation*.

(2) Initializing all bats. In the allowable changing range of the water level of hydropower stations in each time interval, the initial position $X_i^0 =(Z_{1,1}^i, Z_{1,2}^i, \ldots, Z_{1,T+1}^i, \ldots, Z_{N,1}^i, Z_{N,2}^i, \ldots, Z_{N,T+1}^i)$ and speed $V_i^0 =(v_{1,1}^i, v_{1,2}^i, \ldots, v_{1,T+1}^i, \ldots, v_{N,1}^i, v_{N,2}^i, \ldots, v_{N,T+1}^i)$ of the ith bat are generated. In addition, the initial frequency f_i, pulse emission rate r_i^0, and the loudness A_i^0 of pulses are also generated. Where N and T respectively indicate the number of hydropower stations in a cascaded hydropower station group and the total number of calculation time intervals.

(3) Searching the initial best position of bats. According to Formula (14), the annual electricity generation of cascaded hydropower station groups is calculated and used as the initial fitness value $fitness^0(i)$ of bats, so as to find the bat with the maximum fitness value. The corresponding fitness value is assigned to the initial global optimal value, namely, $gbest^0 = \max\{fitness^0(i), i \in [1, n]\}$, thus this spatial position of bats is the best position X_* of the bat population.

$$fitness\,(t) = \begin{cases} f(z) & \text{meet constraints} \\ f(z) - M \cdot K & \text{do not meet constraints} \end{cases} \tag{14}$$

Where $f(z)$, $M \cdot K$, M and K denote the objective function, penalty term, a large positive number and calculation time intervals which do not meet the constraints.

(4) The global update of bats' position. In accordance with Formulas (2) and (3), the position X_i^t and velocity V_i^t of bats are updated, and the bats are checked to confirm whether they are out of the searching range. As for the position and velocity of bats beyond the searching range, they are replaced with the boundary values. Then the updated fitness function value $fitness^t(i)$ is calculated.

(5) The local update of the bat population. A random number R_i^1 with uniform distribution is generated randomly. If R_i^1 is larger than the current pulse

emission rate r_i^t of the ith bat, the current best position X_* generates a new position $Xnew_i^t$ according to the random disturbance in Formula (4), and the fitness function value $fitnew^t(i)$ at the new position is calculated.

(6) Determining whether the locally updated solutions can be accepted or not. Only when the bats met the conditions $fitnew^t(i) > fitness^t(i)$ and $R_i^2 < A_i^t$, they accept the locally updated solutions, namely, $X_i^t = Xnew_i^t$ and $fitness^t(i) = fitnew^t(i)$. Otherwise, these solutions are refused.

(7) Determining the current global optimal solutions. After the global and local updates for bats' positions, the updated fitness value $fitness^t(i)$ of the ith bat is compared with the historical global optimal value $gbest^{t-1}$ of the population. If $fitness^t(i) \geq gbest^{t-1}$, the corresponding fitness values of bats are assigned to the historical global optimal values, namely, $gbest^{t-1} = fitness^t(i)$ and $gbest\_X^{t-1} = X_i^t$. This process is repeated until all bats are compared, and the historical optimal fitness value is updated as the current optimal value, namely, $gbest^t = gbest^{t-1}$ and $gbest\_X^t = gbest\_X^{t-1}$.

(8) Updating the loudness and the pulse emission rate of bats. In accordance with Formulas (5) and (6), the loudness A_i^t and the pulse emission rate r_i^t of the ith bat are updated.

(9) Determining whether the iteration times t has reached the preset maximum iteration times *max_generation*. If not, going back to step (4) to do the calculation again; otherwise, we have our final output, thus the obtained optimal bats are the best optimization strategies of cascaded hydropower station groups.

5. Practical calculation and result analysis

5.1 Optimization calculation and analysis

The Chin-sha River in the upper reaches of the Yangtze River originates from Yushu, Qinghai province and flows 2,326 km to Yibin, Sichuan province in China, showing a drainage area of 473,000 km^2 and a head drop of 3,280 m. This river is divided into the upper, middle and lower reaches. Among them, the section to Shigu, Yunnan province belongs to the upper reach, while the middle reach begins from Shigu to the estuary of Yalong River, from the estuary of Yalong River to Yibin is the lower reach. As the lower reach of the Chin-sha River shows a large head drop of 719 m, a group of four world-class giant cascaded hydropower stations includes Wudongde, Baihetan, Xiluodu and Xiangjiaba are planned. Xiluodu and Xiangjiaba have been constructed and put into production, and they are the second and third largest hydropower stations in China, respectively. In addition, Wudongde has also been approved by executive meetings of the State Council. This study selects the hydropower stations of Xiluodu and Xiangjiaba as the research objects.

Xiluodu hydropower station is a seasonal regulation reservoir with 6.46 billion m^3 of regulation storage. It is mainly used for electricity generation, accompanying with flood control and sediment retention. In addition, the total installed capacity of Xiluodu hydropower station and the multi-year average electricity generation are 13.86 million KW•h and 57.55 billion KW•h, respectively. While Xiangjiaba hydropower station with a regulation storage of 0.903 billion m^3 is an anti-regulating reservoir of Xiluodu hydropower station. Its total installed capacity and the multi-year average electricity generation are 6.4 million KW•h and 30.8 billion KW•h, respectively. In order to meet the demands for flood control and ensure the safety of dams, the water levels of Xiluodu and Xiangjiaba reservoirs from June to August are required to be lower than the limited water levels for flood control, then return to normal in September. The basic parameters of Xiluodu and Xiangjiaba hydropower stations are listed in Table 1.

For the convenience of comparative analysis

Table 1. The basic parameters of Xiluodu and Xiangjiaba hydropower stations

Hydropower stations	Dead water level (m)	Flood control level (m)	Normal water level (m)	Installed capacity (MW)	Maximum Power discharge (m^3/s)	Designed head loss (m)	Power generation coefficient
Xiluodu	540	560	600	13,860	7,922	4.03	8.5
Xiangjiaba	370	370	380	6,400	7,098	1.8	8.8

of the results obtained by using BA, all constraint parameters and runoff data used in the calculation of this study are the same with those in the previous research (Wang *et al.*, 2015). The reservoir inflows and local inflows of 1997-1998 for the calculation are shown in Table 2. The parameters of BA algorithm are set as follows: the number n of bats in the population is 20 and the largest iteration times max_generation is 1,200, with the minimum frequency fmin, the maximum frequency fmax, the initial value A0 of loudness being 0, 2, and 1, respectively. In addition, the attenuation coefficient α of loudness, the maximum pulse emission rate r0, the increase coefficient γ of pulses are 0.95, 1 and 0.95, respectively. Besides, it has been determined through pilot calculation that the minimum generated output of the two hydropower stations needs to be no less than 6,490 MW. In order to eliminate the influences of randomness on the calculation results, the calculation is performed for 50 times independently. The specific calculation results of the best one of the 50 independent solutions are shown in Table 3.

It can be seen from Table 3 that the total generated output of the cascaded hydropower station at each time interval of the scheduling period meet

Table 2. Reservoir inflows and local inflows

Month	6	7	8	9	10	11	12	1	2	3	4	5
The inflows of Xiluodu (m^3/s)	3,831	9,109	7,264	7,766	6,418	2,884	2,212	1,989	1,867	1,931	1,847	3,315
The local inflows of Xiangjiaba (m^3/s)	111	262	209	224	185	83	64	57	54	56	53	96

Table 3. The results of optimal calculation

Month	Xiluodu				Xiangjiaba				Total generated output (MW)
	Inflows (m^3/s)	Month-end water level (m)	Plant discharge (m^3/s)	Waste flow (m^3/s)	Inflows (m^3/s)	Month-end water level (m)	Plant discharge (m^3/s)	Waste flow (m^3/s)	
6	3,831	540.0	3,831	0	3,942	380.0	3,594	0	8,473
7	9,109	560.0	7,922	511	8,695	370.0	7,098	1,934	17,072
8	7,264	570.0	6,900	0	7,109	380.0	6,772	0	16,500
9	7,766	600.0	6,348	0	6,572	380.0	6,572	0	16,902
10	6,418	600.0	6,418	0	6,603	380.0	6,603	0	17,860
11	2,884	600.0	2,884	0	2,967	380.0	2,967	0	8,284
12	2,212	599.4	2,245	0	2,309	380.0	2,309	0	6,491
1	1,989	593.9	2,268	0	2,325	380.0	2,325	0	6,491
2	1,867	585.3	2,319	0	2,373	380.0	2,373	0	6,491
3	1,931	574.7	2,391	0	2,447	380.0	2,447	0	6,490
4	1,847	557.8	2,505	0	2,558	380.0	2,558	0	6,490
5	3,315	540.0	3,909	0	4,005	375.0	4,179	0	9,465

the requirement for the minimum generated output and all of the constraint requirements are satisfied. Xiluodu hydropower station discharges water during dry season and stores water in wet season. The water level and outflow processes conform to the practical operation requirements. Furthermore, the reservoirs are operated to maintain a high water level as far as possible, and the waste water only appears in the months with large inflows during flood season, thus show the optimized results are reasonable. Meanwhile, the calculation takes 2.1 second, so the calculation velocity is satisfactory. Furthermore, the minimum generated output of the cascaded hydropower station (6,490 MW) is significantly higher than the sum (5,859 MW) of the guaranteed generated outputs of Xiluodu and Xiangjiaba hydropower stations, so that BA significantly guarantees the safe and stable operation of the power grid and shows obvious optimization efficiency. In conclusion, solving the multi-objective optimization problem of cascaded hydropower station groups by using BA not only ensures the optimization effectiveness, but also improves the efficiency of calculation.

5.2 The comparison of different methods

In order to test the efficiency and feasibility of BA, the practical calculation results of BA are compared with those of IPGA, RCGA and POA in the previous study (Wang *et al*., 2015). The optimization results acquired by using different methods are shown in Table 4.

From the results of comparisons given in Table 4, it can be inferred that the BA introduced in this study shows significant advantages in solving the multi-objective optimization model of cascaded hydropower station groups. Compared with the results of IPGA, RCGA and POA, the total electricity generations of the two hydropower stations increase by 2.06%, 2.25% and 2.01%, respectively, indicating a favorable optimization effect. In addition, the calculation time of BA is significantly less than that of RCGA, and also slightly less than that of IPGA and POA. Therefore, the BA introduced in this paper exhibits preferable optimization effect, as it not only takes less time to calculate but also shows good convergence, so that it can effectively avoid the problem of premature convergence and acquires satisfactory optimized results.

6. Conclusion

This research establishes a mathematical model by applying the maximization of the total electricity generation while maximizing the minimum generated output of the cascaded hydropower stations as the objective. Based on the model, the authors attempt to search multi-objective optimization operation strategies for cascaded hydropower station groups. Furthermore, the BA is introduced for the multi-objective optimization scheduling model of cascaded hydropower station groups, so as to provide a new solution for the optimization scheduling of cascaded hydropower station. Through the practical calculation of the multi-objective optimization of cascaded hydropower stations Xiluodu and Xiangjiaba on

Table 4. The comparison of the results of optimal operation

Algorithm	Generated energy (10^8 KW•h)			Computational times (s)
	Xiluodu	Xiangjiaba	Total	
BA	595.71	334.93	930.64	2.1
IPGA	578.76	333.12	911.88	2.5
RCGA	577.61	332.08	909.69	11.6
POA	579.12	333.17	912.29	3.8

Chin-sha River, the BA is verified to be reliable and effective. Compared with the results of IPGA, RCGA and POA (Wang *et al*., 2015), the BA has superior efficiency and accuracy. Therefore, the BA introduced in this paper provides a new effective method for solving the multi-objective optimization problems of cascaded hydropower stations.

Acknowledgements

The works was supported by the funding project (973 Program) of National Basic Research Program of China (2013CB036406); National Science and Technology Support Plan (2008BAB29B09); the key projects of National Natural Science Foundation of China (50539140) and the projects of National Natural Science Foundation of China (50679098).

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Received: 105/09/26

Revised: 105/10/31

Accepted: 105/12/12