

Optimal Operation of Cascade Hydropower Stations Based on Chaos Cultural Sine Cosine Algorithm

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Abstract. Due to the fact that Sine Cosine Algorithm(SCA) may easily premature convergence, by taking cultural algorithm as the framework of population space and using chaotic search to lead the evolvement of belief space, a new Chaos Cultural Sine Cosine Algorithm (CCSCA) was present in this paper. And the results of typical benchmark functions show that CCSCA has better global searching ability than SCA to avoid the premature phenomenon. Finally, CCSCA was employed for optimal operation of cascade hydropower stations (OOCHS), and case study showed that CCSCA could get satisfying results with high accuracy and fast efficient, thus providing a new efficient method to solve Oochs.

1. Introduction

In order to respond to the green development requirements for energy conservation and emission reduction, it is very important to optimize the optimal dispatching of cascade hydropower stations and the research of Oochs has attracted wide attention [1]. The main purpose of Oochs is to obtain the maximum power generation benefit during the scheduling period, but the cascade hydropower stations have complex hydraulic and electric connections, and the water level and output has a complex coupling at any time with multi dimensions and multi constraints [2]. The traditional optimization methods include dynamic programming (DP), progressive optimality algorithm (POA) are difficult to solve Oochs. In recent years, plenty of relative algorithms have been present to obtain achievements.

SCA is a population-based stochastic optimization algorithm, and its principle is simple with few controlled parameter [3], but SCA has not yet been employed to Oochs. This research attempts to apply SCA in Oochs after clarifying its operation mechanism, but found SCA is similar with other algorithms to fall into local optimum, so it is necessary to improve the global convergence ability. Therefore, SCA combined with culture algorithm [4] and chaotic search [5] is proposed to form the CCSCA, which used cultural algorithm as the main space in SCA and using chaotic search with local traversal search performance to lead the evolvement of belief space. The test results of several typical test functions show that compared with SCA, differential evolution algorithm (DE) as well as Particle swarm optimization (PSO), the CCSCA proposed in this paper can effectively avoid precocious convergence, and the ability of searching the global optimal solution is significantly improved. Finally, the optimal scheduling of CCSCA is applied to cascade reservoirs, and the feasibility and effectiveness of CCSCA are verified through the comparison and analysis of the scheduling results.

2. Optimal operation model of cascade hydropower stations



According to the main principle of maximizing the total power generation benefit, the mathematical objective function of OOCHS is described as bellow [1][2]:

$$F = \max \sum_{i=1}^N \sum_{t=1}^T A_i \cdot Q_{i,t} \cdot H_{i,t} \cdot \Delta t \quad (1)$$

where N is the number of power station; T is the total periods; A_i is output power coefficient of i -th power station; $Q_{i,t}$, $H_{i,t}$ are respectively the flood discharge volume and water head of i -th power station at t -th period; Δt is the length of period's time. And the constrains of OOCHS are as follows:

(1) Water balance equation:

$$V_t = V_{t-1} + (I_t - Q_t) \Delta t \quad (2)$$

(2) Reservoir upstream water level limit:

$$Z_{i,t}^{\min} \leq Z_{i,t} \leq Z_{i,t}^{\max} \quad (3)$$

(3) Discharge volume limit:

$$Q_{i,t}^{\min} \leq Q_{i,t} \leq Q_{i,t}^{\max} \quad (4)$$

(4) Output power limit:

$$N_{i,t}^{\min} \leq N_{i,t} \leq N_{i,t}^{\max} \quad (5)$$

in Eqs.(2)-(5), $Z_{i,t}^{\min}$ and $Z_{i,t}^{\max}$ are the minimum and maximum upstream water level limit at t -th period; $Q_{t,\min}$ and $Q_{t,\max}$ are the minimum and maximum discharge volume limit at t -th period; $Q_{t,\min}$ and $Q_{t,\max}$ are the minimum and maximum output power limit at t -th period.

3. Chaos Cultural Sine Cosine Algorithm (CCSCA)

3.1. Sine Cosine Algorithm (SCA)

The population of SCA contains N D -dimensions real-valued parameter vectors in the population [3]. In t generation, the position of i individual is the vector $\mathbf{X}_i(t) = (x_{i1}(t), x_{i2}(t), \dots, x_{iD}(t))$, and the global optimal location in population so far is expressed as $\mathbf{P}_g(t) = (p_{g1}(t), p_{g2}(t), \dots, p_{gD}(t))$. And the vector updating is determined by the following equations:

$$\begin{aligned} \mathbf{X}_i(t+1) &= \mathbf{X}_i(t) + r_1 \times \sin(r_2) \times |r_3 \cdot \mathbf{P}_g(t) - \mathbf{X}_i(t)|, \quad r_4 < 0.5 \\ \mathbf{X}_i(t+1) &= \mathbf{X}_i(t) + r_1 \times \cos(r_2) \times |r_3 \cdot \mathbf{P}_g(t) - \mathbf{X}_i(t)|, \quad r_4 \geq 0.5 \end{aligned} \quad (6)$$

where r_1 , r_2 , r_3 and r_4 are random numbers, and $r_1 = 2 \times (1 - t/G)$, $r_2 \in [0, 2\pi]$, $r_3 \in [0, 2]$, $r_4 \in [0, 1]$, and their specific utilities are mentioned as follows: r_1 defines the next position's region, which could be either in or outside the space between the solution and destination; r_2 indicates the movement towards or outwards the destination; r_3 indicates a random weight for the destination in order to stochastically emphasize ($r_3 > 1$) or deemphasize ($r_3 < 1$) the effect of destination in defining the distance; r_4 equally switches between the sine and cosine components.

3.2. Chaos Cultural Sine Cosine Algorithm (CCSCA)

The framework of Cultural algorithm is shown in Fig. 1, which includes three components, i.e. a population space for producing knowledge, a belief space for using knowledge as well as a communication protocol for exchanging information of the two spaces [4]. Any population based algorithm can be adopted as the evolution process of population space. Then, belief space selectively accepts the knowledge, and uses the knowledge to adjust its knowledge structure so as to guide population space evolution in next generation. Here chaotic search [5] is adopted in the belief space. Finally, the communication protocol is implemented by the accept operation and influence operation.

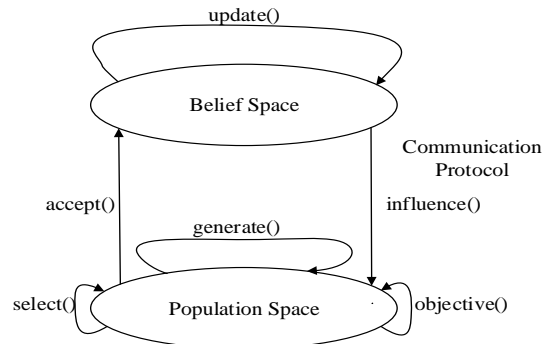


Figure.1 Framework of cultural algorithm

The specific procedures for accept operation and influence operation are as follows: (1) accept operation. Set the size of belief space is $M = 0.2N$, population space provides the better M individuals for belief space, then the belief space takes the better M individuals to replace itself by comparing the fitness value. (2) Influence operations. The belief space chooses the better M individuals to replace the individuals in population space. In this paper, CCSCA employs the two operations every 20 generations.

For any individual $\mathbf{X}_i(t) = (x_{i1}(t), x_{i2}(t), \dots, x_{iD}(t))$ in belief space, when the maximum number k_{\max} of local chaotic searches is given, the specific flow of chaotic local search is as follows [5]:

Step 1: Set $k = 1$, a chaotic sequence $\mathbf{cx}^k = (cx_1^k, cx_2^k, \dots, cx_D^k)$ is produced with improved logistic chaotic map written as $cx_j^{k+1} = 1 - 2 \cdot (cx_j^k)^2$, here $j = 1, 2, \dots, D, k = 1, 2, \dots, k_{\max}$ and $cx_j^k \in [-1, 1]$.

Step 2: Two new individuals $\mathbf{c}_i(t) = (c_{i1}(t), c_{i2}(t), \dots, c_{iD}(t))$ and $\mathbf{r}_i(t) = (r_{i1}(t), r_{i2}(t), \dots, r_{iD}(t))$ are achieved based on $\mathbf{X}_i(t)$ and the optimal location $\mathbf{P}_g(t)$ for chaotic search as follows:

$$c_{ij}(t) = cx_j^k \cdot p_{gj}(t) + (1 - cx_j^k) \cdot x_{ij}(t), \quad j = 1, 2, \dots, D \quad (7)$$

$$r_{ij}(t) = cx_j^k \cdot x_{ij}(t) + (1 - cx_j^k) \cdot p_{gj}(t), \quad j = 1, 2, \dots, D \quad (8)$$

Step 3: Calculate the fitness values of the two new individual and find the better individual from them called $\mathbf{cr}_i(t)$. Moreover, compare the fitness values between $\mathbf{X}_i(t)$ and $\mathbf{cr}_i(t)$, and replace $\mathbf{X}_i(t)$ by $\mathbf{cr}_i(t)$ if the fitness value of $\mathbf{cr}_i(t)$ is better than $\mathbf{X}_i(t)$.

Step 4: Set $k = k + 1$, if $k > k_{\max}$, then the chaotic local search is stopped, otherwise turn to **Step 1**.

3.3. Flowchart of CCSCA

With the basic SCA and the improvements, the flowchart of CCSCA proposed is as follows:

Step 1: Initialization. Set generation $g = 0$, and initialize the population space and belief space.

Step 2: Implement the SCA operation for each individual with Eq.(6) in population space.

Step 3: If the generation reaches the specified item, accept operation and impact operation would be proceeded between population space and belief space.

Step 4: If g equal the given condition, export the optimal solution, otherwise $g=g+1$, turn **Step 2**.

4. Benchmark Function Tests

In order to demonstrate the effectiveness of CCSCA, four well-known Benchmark functions with their global optimum value are mentioned in Table 1. Additionally, SCA, DE and PSO are used to show the improvement of the proposed algorithm.

Table1 benchmark functions

Function	Expression	Dim	Shift position	optimal value
Sphere	$f_1(x) = \sum_{i=1}^D x_i^2$	30	[-100,100]	0
Schwefel	$f_2(x) = \sum_{i=1}^D (\sum_{j=1}^i x_j)^2$	30	[-100,100]	0
Rastrigin	$f_3(x) = \sum_{i=1}^D [x_i^2 - 10 \cos(2\pi x_i) + 10]$	30	[-5.12,5.12]	0
Griewank	$f_4(x) = \frac{1}{4000} \sum_{i=1}^D x_i^2 - \prod_{i=1}^D \cos(\frac{x_i}{\sqrt{i}}) + 1$	30	[-600,600]	0

The parameters of SCA and CCSCA are $NP=100$, $D=100$, $Gmax=1000$. The parameters of DE is $F=CR=0.4$. The parameters of PSO is $w_{\max}=0.9$, $w_{\min}=0.2$, $c_1=c_2=2$. The test results are shown in table 2 and each function is independently processed 50 times. And the convergence curves for each function are respectively shown in Fig.2-Fig.7.

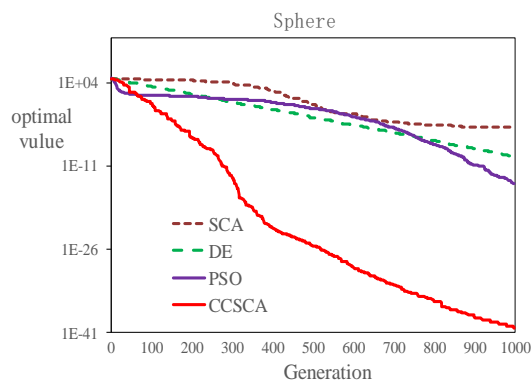


Figure.2 Convergence curve of function Sphere

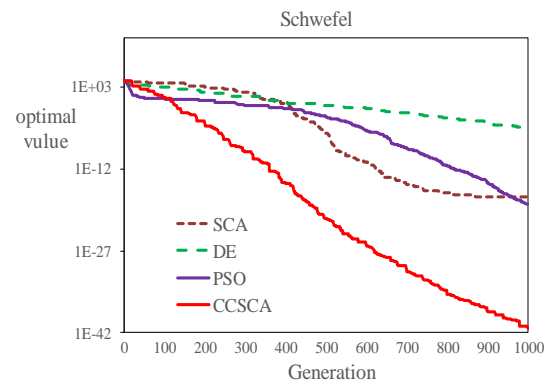


Figure.3 Convergence curve of function Schwefel

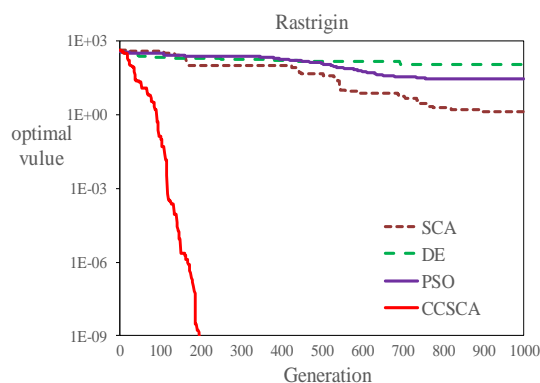


Figure.4 Convergence curve of function Rastrigin

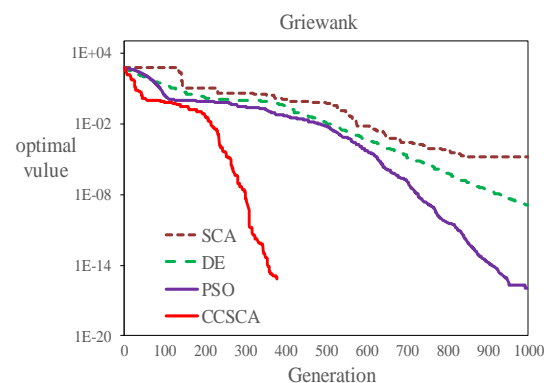


Figure.5 Convergence curve of function Griewank

Seen from **table 2** and **Fig.2-Fig.5**, CCSCA outperforms SCA, DE and PSO in solving all functions, and CCSCA can avoid premature effectively and get better convergence precision.

Table2 Test function results for SCA, DE, PSO and CCSCA

function	Algorithm	best	worst	average	standard deviation
Sphere	SCA	5.1467e-08	1.0642e-04	3.8457e-05	4.3636e-05
	DE	2.3862e-10	5.2235e-10	3.4644e-10	1.4131e-10
	PSO	2.1439e-17	6.4129e-15	2.5669e-15	3.3807e-15
	CCSCA	7.0495e-46	1.4926e-39	4.8565e-40	6.6848e-40
Schwefel	SCA	3.4311e-24	9.4549e-18	3.2041e-18	5.4139e-18
	DE	2.9124e-05	3.9115e-05	3.3415e-05	5.1423e-06
	PSO	1.3736e-21	6.5816e-19	3.2738e-19	3.2842e-19
	CCSCA	6.8903e-42	1.5377e-34	5.1270e-35	8.8767e-35
Rastrigin	SCA	9.7101e-08	29.2436	11.7733	15.5131
	DE	117.8569	146.8859	129.0434	13.9066
	PSO	29.8487	74.8625	53.9890	17.0591
	CCSCA	0	0	0	0
Griewank	SCA	6.5608e-06	0.0027	8.9970e-04	0.0015
	DE	7.0845e-10	5.1065e-09	2.3265e-09	2.4183e-09
	PSO	0	0.0172	0.0057	0.0099
	CCSCA	0	0	0	0

5. Case study of OCHS based on CCSCA

Yalong river is the largest tributary of Jinsha river, which is extremely rich in hydraulic resources. It has planned 22 hydropower stations with annual capacity of about 150 billion kW·h, and has outstanding features, such as abundant water resources, good regulation performance and superior economic indicators. Moreover, the lower reaches of Yalong river is the key section of hydropower development of Yalong river, including five hydropower stations with installed capacity 14.7 million kW from upstream to downstream, i.e. Jinping1, Jinping2, Guandi, Ertan and Tongzilin, which have been put into operation since 2015, and their characteristic parameters are put forward in Table 3, thus the management mode of cascade hydropower stations in modern watershed is basically formed.

Table 3. Characteristic parameters of cascade hydropower stations

Number	Hydropower station	Normal level (m)	Regulation volume ($10^8 \cdot m^3$)	Regulation performance	Guaranteed output(million kW)
1	Jinping1	1880	49.1	Year	3.6
2	Jinping2	1646	0.0496	Day	4.8
3	Guandi	1330	1.232	Day	2.4
4	Ertan	1200	33.7	Season	3.3
5	Tongzilin	1015	0.146	Day	0.6

In order to verify the efficiency of CCSCA, we have a case study on the OCHS of 5 hydropower stations located in the lower reaches of Yalong river, and water level of each hydropower station at each period is adapted as the optimal variable in SCA and CCSCA. The scheduling period is one year, the schedule time is one month, so the total time period is 12, and the beginning and end water level are normal level. For the daily regulation power station, the storage capacity of Jinping2, Guandi, and Tongzilin are not considered, only their water heads are considered for generation. And the parameters of SCA and CCSCA are $NP=100$, $D=24$, $G_{max}=1000$.

Based on the basic data and runoff data, the typical inflow process in the wet year was selected for maximum power generation calculation, and the results of the two algorithms are shown in table 4. The calculation result of total power generation of CCSCA is better than SCA, which improves the solution precision and indicates that CCSCA can be better applied to practical engineering practice.

Furthermore, Fig. 6 and Fig.7 show the water level and output power of Jinping1 and Ertan hydropower station, it is obvious that the optimization results of CCSCA meet the various constraints, and the scale efficiency and compensation efficiency of cascade hydropower stations are fully utilized.

Table 4. The comparing power generation benefit of SCA and CCSCA

Algorithm	Jinping1	Jinping2	Guandi	Ertan	Tongzilin	Total(million kW·h)
SCA	195.6	284.3	129.6	199.1	34.5	843.1
CCSAC	195.9	285.1	129.8	200.2	35.8	846.8

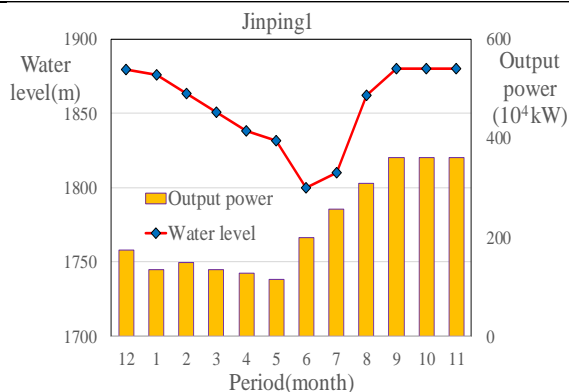


Figure.6 Optimal results of CCSCA for Jinping1

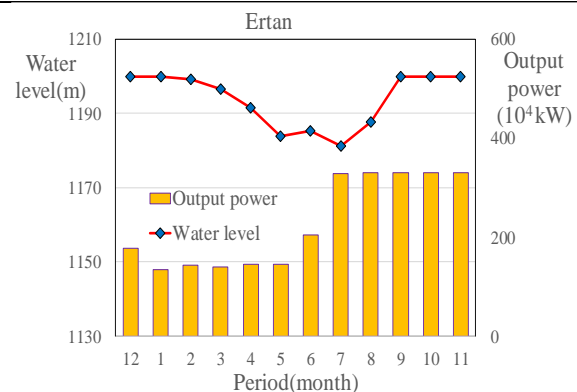


Figure.7 Optimal results of CCSCA for Ertan

6. Conclusions

In this paper, Chaos cultural sine cosine algorithm (CCSCA) is proposed by taking cultural algorithm as the framework of population space and using chaotic search to lead the evolvement of belief space. benchmark function tests prove that CCSCA has excellent ability and strong robustness. And case study on the lower reaches of Yalong river indicates that CCSCA provides a new way for optimal operation of cascade hydropower stations (OOCHS).

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