A Minimal Water power Loss Model Based on Annealing Genetic Algorithm in Optimal Operation of Cascade Reservoirs

Chunming Ouyang1,*
1Electric Power Research Institute of Guangdong Power Grid Co., Ltd., Guangzhou, Guangdong, China

*Corresponding author e-mail: olivia89@foxmail.com

Abstract. The problem of power stations optimal operation based on cascade as a whole is rather complicated. In this article, minimal total power loss is taken as the objective in the optimal operation modeling of Cascade Reservoirs. Annealing genetic algorithm is adopted for a solution and the Cascade Reservoirs is taken as an example for calculation. Results show that the model could effectively improve the utilization of clean power from cascade reservoirs, providing a new thinking for optimal operation.

1. Introduction
Optimal operation of Cascade Reservoirs is an important part in optimized operation of electric power system. The power dispatching center makes daily load plans for cascade hydropower plants in a way of “direct dispatching of cascade”. With the balance of pure output from hydropower system and hydropower load ensured, cascade hydropower plants, based on the power regimen in the watershed and actual situation of those plants, optimizes the power consumption of reservoirs with ability to regulate by allocating the total load to cascade hydropower plants for the second time in the principle of economy and safety.

Under the premise of meeting the overall load plan of the whole cascade, the research on the optimal operation of Cascade Reservoirs pays more attention on the reasonable utilization of station in each reservoir to generate power. Many constraints are involved, requiring the establishment of more complicated mathematical model. In existing research fruits, the mathematical model for optimal operation of Cascade Reservoirs takes the minimal power consumption [1], minimal discarded power [2] and highest power level at the end of a day [3] as the optimization objectives. There are certain limitations more or less in those objectives. In this article, for energy saving and consumption reduction, minimal total power loss is taken as the objective in mathematical modeling of optimal operation of Cascade Reservoirs.

2. Optimal operation Modeling
Reservoirs in the cascade are not only connected with power. used for power generation from reservoirs upstream could be reused in downstream and in comparison with power in downstream, it has higher potential energy. Minimal power loss requires downstream reservoirs arrange to generate power as much as possible while upstream retain the power of higher potential energy so as to achieve the goal of cascade economical operation. Thus, for the purpose of minimal cascade power loss, with
constraints of cascade reservoirs operation taken into account, a mathematical model is established as follows:

### 2.1. Objective Function

\[ E = \min \left( \sum_{t}^{T} \sum_{i}^{S} \sum_{j}^{\infty} \eta_{j} \cdot h_{i,j} \cdot Q_{j,t} \right) \Delta t_{i} \]  

(1)

Where \( E \) is the total power loss of \( i \) reservoirs during \( T \) periods (kWh); \( \eta_{j} \) is the output coefficient of reservoir \( j \); \( h_{i,j} \) is the water head (m) of reservoir \( j \) in period \( t \); \( Q_{j,t} \) is the discharge of reservoir \( j \) in period \( t \) (m³/s); \( \Delta t_{i} \) is the length (h) of period \( t \); \( T \) is the total number of periods in calculation period; \( S \) is the number of cascade reservoirs; \( t \) is the time phase number; \( i \) and \( j \) is the reservoir number, \( i=1,2,\ldots,S; \ j=i,i+1,\ldots,S \).

### 2.2. Constraints

According to the actual requirements of economical operation of cascade reservoirs, following constraints shall be taken into account in modeling:

1. **Output balance equation:** the economical operation of cascade reservoirs must ensure the completion of power generation. Hence, total output of cascade shall equal to the output in each period.

\[ \sum_{j=1}^{S} P_{i,j} = P_{t} \]  

(2)

Where \( P_{i,j} \) is the output of reservoir \( i \) in period \( t \), unit: MW; \( P_{t} \) is the required total output of cascade reservoirs in period \( t \), unit: MW.

2. **Reservoir output constraints:** to ensure the safe operation of reservoirs, reasonable and practicable power generation plan for economical operation, output of each reservoir shall be within acceptable range.

\[ P_{i,j}^{\text{min}} (h_{i}) \leq P_{i,j} \leq P_{i,j}^{\text{max}} (h_{i}) \]  

(3)

Where, \( P_{i,j}^{\text{min}} (h_{i}) \) and \( P_{i,j}^{\text{max}} (h_{i}) \) are the minimal output and maximal output of reservoir \( j \) when water head is \( h_{i} \), unit: MW.

3. **Water budget constraint:** the impoundment of reservoir is related to the impoundment, inflow and discharge at the last period.

\[ V_{i+1,j} = V_{i,j} + \Delta t_{i} \cdot (Q_{i,j}^{\text{in}} - Q_{i,j}^{\text{out}} - \dot{q}_{i,j}) \]  

(4)

Where \( V_{i,j} \) refers to the impoundment of reservoir \( i \) at the beginning of period \( t \), unit: m³; \( V_{i+1,j} \) refers to the impoundment of reservoir \( i \) at the end of period \( t \), unit: m³; \( Q_{i,j}^{\text{in}} \) refers to the total inflow of reservoir \( i \) at the period \( t \), unit: m³/s; \( Q_{i,j}^{\text{out}} \) is the outflow of reservoir \( i \) at the period \( t \), unit: m³/s; \( \dot{q}_{i,j} \) is the waste water of reservoir \( i \) at the period \( t \), unit: m³/s.

4. **Water flow connection amongst cascade reservoirs:** inflow of cascade reservoirs consists of discharge from reservoirs from upstream and regional inflow. Besides, flow stagnation between reservoirs shall be taken into account.

\[ Q_{i,j}^{\text{in}} = Q_{i+1,j}^{\text{out}} + q_{i,j} \]  

(5)
Where: $Q_{it}^{in}$ refers to the total inflow of reservoir $i$ at the period $t$, unit: m$^3$/s; $Q_{t-\tau}^{out,i}$ is discharge from upper reservoir at period $t-\tau$, unit: m$^3$/s; $q_{t,i}$ is the regional inflow of reservoir $i$ in period $t$, unit: m$^3$/s; $\tau$ is the flow stagnation between reservoirs.

(5) Reservoir impoundment constraint: to ensure the safe operation of reservoirs, reservoir impoundment must meet the upper and lower limits requirements.

$$V_{i}^{min} \leq V_{i,t} \leq V_{i}^{max}$$

Where, $V_{i}^{min}$ is the lower limit of impoundment of reservoir $i$, namely, the dead reservoir capacity or minimal impoundment for comprehensive utilization, unit: m$^3$; $V_{i}^{max}$ is the upper limit of impoundment of reservoir $i$, namely, the reservoir’s normal impounded level or impoundment of flood control level in flood period, unit: m$^3$.

(6) Discharge constraint

$$Q_{i}^{min} \leq Q_{t,i} \leq Q_{i}^{max}$$

Where, $Q_{i}^{min}$ is the lower limit of outflow from reservoir $i$ in period $t$ as the minimal water discharge for power generation required by the water turbine or comprehensive water utilization, unit: m$^3$/s; $Q_{i}^{max}$ is the upper limit of outflow from reservoir $i$ in period $t$ as the maximal water discharge for power generation required by the water turbine or power station, unit: m$^3$/s;

(7) Other constraints: including unit startup and shutdown constraint, joint avoidance vibration area, dynamic characteristic of unit, etc.

3. Algorithm

Minimal power consumption model for economical operation of cascade reservoir adopts annealing genetic algorithm [4, 5] to look for a solution.

Annealing genetic algorithm is the combination of genetic algorithm and simulated annealing, in which, annealing search of population is carried out after genetic manipulation to improve the accuracy of genetic algorithm. Meanwhile, genetic manipulation accelerates the calculation speed of simulated annealing. During coding calculation individuals, outputs of reservoirs in different time interval shall be chosen as the coding variable to achieve the uniformly-spaced dispersing of spans of all coding variables, represented by real number coding. Therefore, each calculation individual corresponds to a load distribution plan. Steps for annealing genetic algorithm are shown in figure 1.

Step 1: Parameter initialization, including annealing coefficient $\alpha$, required precision $E$, population scale, penalty factor, etc;

Step 2: Random generation of initial prospective population $Pop_0^'$ with scale of $n$ and constraints satisfied;

Step 3: Calculate the adaptability and selective probability of initial prospective population $Pop_0^'$, and rank in descending order of selective probability, followed by selective probability accumulation and normalization.

Step 4: Genetic manipulation, including selection, crossing, variation of prospective population to obtain the initial population $Pop_0$, followed by the elective probability accumulation and normalization of each individual;

Step 5: Confirmation of initial temperature. The best and worst in $Pop_0$ shall be recorded as $P_C$ and $P_W$, then confirm the initial annealing temperature $T_0 = |P_C - P_W|/n$;

Step 6: Inspection of convergence condition. Check whether $e < E$ or $N > 200$ is established or not. If established, skip to Step 15, otherwise, follow Step 7;

Step 7: Make $No_c = 0$ and $N = N + 1$;
Step 8: Check whether \( \text{No.} > n \) is established or not. If established, skip to Step 13, otherwise, follow Step 9;

Step 9: Annealing search. Roulette is adopted to select the annealing search starting point \( P_c \) from the population and then carry out dynamic disturbance to generate new individual \( P_{new} \);

Step 10: Annealing calculation. Calculate the difference between \( P_{new} \) and the objective function of the present individual by \( \Delta f = f(P_{new}) - f(P_c) \), and calculate the selective probability of \( P_{new} \) by \( p_r = \min[1, e^{-\Delta f/T_r}] \);

Step 11: Annealing inspection. Generate a random number \( Rnd \), then judge whether \( p_r > Rnd \) is established or not. If established, follow Step 12, otherwise, repeat Step 9;

Step 12: Acceptance of new individual. Add the new individual into the \( k + 1 \) generation of prospective population \( Pop_{k+1} \), and make \( P_c = P_{new} \), \( \text{No.} = \text{No.} + 1 \), then repeat Step 8;

Step 13: Genetic manipulation, including selection, crossing, variation of the prospective population \( Pop_{k+1} \) to obtain the \( k + 1 \) generation of population \( Pop_{k+1} \), followed by the selective probability accumulation and normalization of each individual;

Step 14: Population evaluation. The individual with the highest adaptability in \( Pop_{k+1} \) shall be recorded as \( P_B \), make \( T_{k+1} = T_k \times \alpha \), \( k = k + 1 \), \( e = |f(P_B) - f(P_0)| \), \( P_0 = P_B \) and then repeat Step 6;

Step 15: Output of results.

4. Calculation Example

Based on above model and algorithm, Cascade Reservoirs in watershed P is taken for analysis and calculation. According to planning, watershed P consists of “one reservoir and three levels of power plants”, falling into A, B and C with total installed capacity of 300MW.

Now A reservoir’s inflow in the next day is known as 12m³/s, interval inflow between A and B as 7m³/s, B and C as 6m³/s, initial levels of the reservoir are 2250m, 2032m and 1543m, respectively, scheduling period of one day. Taking 15min as the unit, the period is divided into 96 periods. P cascade reservoir next-day planned output curve issued by the dispatching center is as shown in Figure 1. As a result that cascade reservoirs are run-of-river power stations and end-to-end connected, flow stagnation between each two cascade reservoirs is very small and could be neglected. C language programming is used for optimal operation calculation of Cascade Reservoirs in watershed P with optimization results as shown in Figure 2 - 5.
Figure 1. Steps for annealing genetic algorithm
Figure 2. Expected output of cascade hydropower plants versus time

Figure 3. Output of hydropower plant A versus time

Figure 4. Output of hydropower plant B versus time
Figure 5. Output of hydropower plant C versus time

In annealing genetic algorithm, each reservoir’s output is taken as the optimized variable, minimal total system energy consumption as the objective. 50 individuals are iterated for 200 generations with crossover probability and mutation probability of 0.7 and 0.02 respectively. The total generating capacity of cascade reservoirs cluster in watershed P is 2,975.00MW.h, 280.00MW.h from A, 1423.75MW.h from B and 1271.25MW.h from C, consumption is 564,000 m3. Waste of is not discovered in those power plants.

From analysis of above optimization calculation results, we can know that with the same amount, reservoirs at the upstream have a higher potential than that in the downstream. Therefore, when optimal operation model of Cascade Reservoirs is allocating on cascade planned output curve, first, C reservoir shall be arranged to generate power as soon as possible and remaining load will be arranged to B reservoir. In case that both reservoirs cannot meet the requirements of the cascade load, the load could be arranged for A reservoir. For the minimal power consumption, from upstream reservoirs shall be saved while priority shall be given to downstream reservoir for significant economic benefits.

5. Conclusion

According to the characteristics of cascade reservoirs, in this article, from the angle of energy saving, the cascade reservoir economic operation model for the purpose of minimal total power loss is researched, using annealing genetic algorithm to solve the model, and good results are achieved. Calculation examples of P cascade reservoirs show that this model can make rational use of resource and provide an idea model for optimal operation of Cascade Reservoirs.

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References

[1] A.Q. Li, L.P. Wang, C.H. Li, C.M. Ji, W.W. Li. The optimized loading distribution among cascaded hydropower stations based on immune particle swarm optimization algorithm [J]. Journal of Hydroelectric Engineering, 2007, 26(5): 15~20.
[2] W.L. Yuan, Q. Huang, Y.M. Wang, H.T. Wu, Z. Liu. Application of minimal abandoned model in optimal operation of cascade reservoirs [J]. Journal of Hydroelectric Engineering, 2008, 27(3): 16~21.
[3] L.S. Yang, R.H. Xu. The Daily Load Optimal Distribution Study on Cascaded Hydroelectric Stations [J]. Journal of Henan Education Institute (Natural Science),2001,10(4):30～33.
[4] C.P. Cheng. Unit commitment by annealing genetic algorithm [J]. Electrical Power and Energy Systems,2002, 24(2): 149~158.
[5] Z.G. Wang, Y.S. Wong, M. Rahman. Development of a parallel optimization method based on genetic simulated annealing algorithm [J]. Parallel Computing, 31(2005): 839~857.