Study on load distribution and operation chart of energy storage for cascade hydropower stations

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ABSTRACT:

With a large number of cascade hydropower stations are developed in recent decades, the management pattern of the joint operation is formed. As a result, the joint operation for large-scale cascade hydropower stations is facing a series of problems. However, shortcomings and deficiencies are still existed among existing optimization algorithms, especially in solving optimal problem of large-scale complex cascade hydropower system. Also, the uncertainty of reservoir runoff is another problem that leads to the optimizing operation model is difficult to use in the actual operation. Thus, in order to improve the comprehensive economic benefits of the cascade hydropower system, it has a theoretical and practical value to study cascade operation theory in line with practical needs. In this paper, a joint operation rules about load distribution and energy storage operation chart for cascade hydropower stations is proposed. Firstly, a cascade storage energy maximum model is established and the method of coupling water storage rate and discriminant coefficient is developed to solving this model. Then combined with the cascade load distribution method, the method of drawing the cascade storage operation chart is studied. Finally, compared with several previous methods, the simulation results of this method can get better solutions with smaller water cost, which proves it is an alternative method to deal with this kind of problem.

1 INTRODUCTION

In recent years, with the cascade development of hydropower in the basin, the operation and management mode of hydropower station has gradually changed from a single power station to a new mode of joint operation and management of cascade hydropower system in the whole basin or even across basins. Due to series and parallel relationship between the upstream and downstream hydropower stations in the basin, hydrological characteristics, regulation capacity and complex crisscross of hydraulic and electric contact, make the formulation of cascade joint operation rules become more complicated and difficulties. At the same time it needs to consider some constraints, such as the reservoir water balance, water level and capacity, the output, the discharge and cascade power generation reliability and total output. And it also has various questions, such as the choice of the objective function, the processing of constraint conditions, the solving is difficult, the inflow is unpredictability and the practical application. Although many optimal operation theories and models have been applied to the joint operation of cascade hydropower systems, and some research results have been obtained (e.g. Ruey-Hsun and Yuan-Yih,1995; Shyh-Jier,1998; Kumar,2013). However, due to the uncertainty of inflow from each reservoir, many optimization theories cannot be well applied to meet the operation needs of the actual hydropower system.

At present, the research on the formulation of joint operation rules for cascade hydropower system mainly focuses on two aspects: first, the determination of the total output for the cascade (Liu et al.,2009; Ji et al.,2014), which can be realized by the operation chart and the operation function of the total output for the cascade; Second, the distribution of total output among cascade hydropower stations is generally solved by the discriminant coefficient method (Xie,2005) and the reservoir capacity efficiency index method (Bellman and Zadeh,1970). But the two existing distribution methods of the total output have shortcomings. The reservoir capacity efficiency index method in the distribution of cascade total output, without considering the energy gains and losses of its upstream and downstream stations when the current power station is water storage or supply, makes the evaluation of the energy gains and losses is not accurate. And it is no better to achieve the purposes of maximum cascade reservoirs energy storage. Although discriminant coefficient method based on the purpose of maximum cascade energy storage at the end of period, in considering the constraint conditions of discharge, output and capacity in the actual operation of the cascade reservoirs, it will lead to the downstream reservoir unnecessarily abandoned water in the water storage of future period and reduce the power generation of the cascade reservoirs, lead to the upstream reservoir excessive empty with depth damage in the water supply of future period , and lost regulation ability and increase the generation risk rate of the cascade system.

The aim of this paper is to develop a cascade load distribution method, coupled with the water storage rate and the discriminant coefficient method in the formulation of joint operation rules for cascade hydropower system. The rest of this paper is organized as follows: in Section 2, the maximum total energy storage model of cascade and its solution are presented in this study, followed by a cascade joint operation based on operation chart of energy storage are presented in Section 3. Then case study is showed in Section 4. Conclusion is drawn in Section 5.

2 THE MAXIMUM TOTAL ENERGY STORAGE MODEL OF CASCADE AND ITS SOLUTION

2.1 *The maximum total energy storage model of cascade*

To ensure complete total energy (or total output) of cascade in each period as the premise, on the basis of considering constraint conditions of each cascade station, the maximum total energy storage mode of cascade is adopted for total load distribution. Thus, the water consumption for power generation is reduced and the utilization efficiency of water resources is improved, which is beneficial to the improvement of comprehensive power generation benefit of cascade hydropower system.

(1) Objective function

$$Ob\text{:}\quad F_t = Max\sum_{m=1}^{M}\left\{\left[V_m^t - V_{dead}\left(m\right)\right]\times\sum_{i=m}^{M}k_i h_i^t\right\} \tag{1}$$

$$St\text{:}\sum_{m=1}^{M}N_m^t = \sum_{m=1}^{M}k_m Q_m^t h_m^t = N_{s,t}\quad\left(t=1,2\cdots T\right) \tag{2}$$

Where t is the monthly time step, T is the total allocation period, M is the total hydropower stations of cascade, F_t is the total energy storage of cascade at the end of t-th period, $N_{s,t}$ is the total output of cascade at t-th period, N_m^t is the output of the m-th power station at t-th period, k_i is the output coefficient of i-th power station, V_m^t 、 $V_{dead}\left(m\right)$ are the reservoir volume at t-th period and the minimum reservoir volume of m-th station respectively, Q_m^t is the discharge of m-th station at t-th period, h_i^t is the water head corresponding to the available water of i-th power station at t-th period.

(2) Constraint conditions

1) Water balance equation

$$V_i^{t+1} = V_i^t + \left(I_i^t - Q_i^t\right)\Delta t \tag{3}$$

2) Reservoir volume limit

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

3) Discharge limit

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

4) Output limit

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

5) Reliability requirement limit of power generation

$$\mathrm{P} \ge P_s \tag{7}$$

Where in Eqs.(3)-(7), V_i^{t+1} and V_i^t are the reservoir volume of *i*-th station at *t*-th and *t+1*-th period respectively, I_i^t is the inflow of *i*-th station at *t*-th period, Q_i^t is the discharge of *i*-th station at *t*-th period, Δt is the time of one period, $V_i^{t,min}$ and $V_i^{t,max}$ are the minimum and maximum reservoir volume of *i*-th station at *t*-th period, $Q_i^{t,min}$ and $Q_i^{t,max}$ are the minimum and maximum discharge of *i*-th station at *t*-th period, $N_i^{t,min}$ and $N_i^{t,max}$ are the minimum and maximum output of *i*-th station at *t*-th period, P is the reliability requirement of power generation for the joint operation of cascade hydropower system, P_s is the lower reliability requirement of power generation for the actual demand.

2.2 *The water storage rate and discriminant coefficient*

Although the energy of each power station can be distributed at will during the joint operation of cascade hydropower system, it is necessary to formulate a reasonable joint operation mode, to determine the order of water storage and release in each reservoir, so as to maximize the benefit of cascade total power generation. This paper from the perspective the power generation benefit of cascade hydropower stations and water quantity control, developed a load distribution method of coupling water storage rate and discriminant coefficient. The purpose is to use the compensation regulation of cascade reservoirs, ensure that the cascade hydropower system will not be a large amount of abandoned water in the future storage period as far as possible, and will be the stability and continuity of power supply to prevent the deep damage in extreme weather in the future supply period, so as to make the water resources distribution of cascade reservoirs more reasonable.

When the total output N_s is obtained in a given period during the joint operation of the cascade hydropower system, it shall be reasonably distributed among the cascade power stations, and then the operation of each power station shall be implemented separately. There is a balance equation: $N_s = \sum N_i$, where N_i is the distributed output of *i*-th power station. When N_s is certain, there are countless ways to distribute output to satisfy this equation, but there is only one most reasonable way to maximize the final total energy storage of cascade hydropower system. When the parameters and inflow of each power station at the beginning of the current period are known, the sum of reservoir non-storage and non-supply output N_q of each power station, which generating power all from the inflow is compared with the given total output N_s at one period, there are the following three situations:

① When $N_q > N_s$, it indicates that the given total output N_s is completely provided by the inflow of cascade hydropower system at current period, and there is still excess inflow. The reservoirs in the cascade hydropower system should be stored water for use in the future period.

② When $N_q < N_s$, it indicates that the inflow of cascade hydropower system at current period cannot provide the given total output N_s, and the reservoirs in cascade hydropower system should use the stored water to meet the total power demand.

③ When $N_q = N_s$, it indicates that the inflow of cascade hydropower system at current period can meet the given total output, and the reservoir does not store water or supply water.

(1) Determination of water storage order of hydropower stations

At a certain period, the cascade hydropower system can meet the given total output N_s, and when $N_q > N_s$, the cascade hydropower system should store water, assuming that the energy ΔE_x is stored by *i*-th reservoir, then

$$\Delta E_x = 0.00272 \cdot \eta \cdot F_i \cdot DH_i \cdot \sum_{j=i}^{M} H_j \tag{8}$$

Where F_i is the average reservoir area at current period, η is the generation efficiency of *i*-th power station, DH_i is the increased water head when the current *i*-th station stored water, $\sum_{j=i}^{M} H_j$ is the sum of power generation heads of current *i*-th power station and its downstream cascade.

Due to the increase of water head DH_i caused by the water storage of *i*-th reservoir, the additional energy of cascade hydropower system will be increased in the following two parts. The first increased water energy ΔE_w is caused by the power generation of *i*-th hydropower station with the incoming water W_i at current period. The second increased water energy ΔE_v is caused by the sum of the available water $\sum_{j=1}^{i-1} V_j$ in the upstream of *i*-th reservoir in the cascade hydropower system. The calculation formula can be expressed as follow:

$$\Delta E_w = 0.00272 \cdot \eta \cdot W_i \cdot DH_i \tag{9}$$

$$\Delta E_v = 0.00272 \cdot \eta \cdot \sum_{j=1}^{i-1} V_j \cdot DH_i \tag{10}$$

Therefore, the increased energy of cascade hydropower system at the end of the period when *i*-th reservoir stores unit energy is:

$$K_i = (\Delta E_w + \Delta E_v)/\Delta E_x = \left(W_i + \sum_{j=1}^{i-1} V_j\right) \Big/ \left(F_i \cdot \sum_{j=i}^{M} H_j\right) \tag{11}$$

It can be seen from the calculation method of *K* value that reservoirs with large *K* value in storage period store water first, namely, the larger the K value of the same energy stored in reservoirs, the more the total energy of cascade hydropower system increases.

(2) Determination of water supply order of hydropower stations

At a certain period, the cascade hydropower system can meet the given total output N_s, and when $N_q < N_s$, the cascade hydropower system should supply water, assuming that the energy ΔE_x is supplied by *i*-th reservoir, then

$$\Delta E_x = 0.00272 \cdot \eta \cdot F_i \cdot DH_i \cdot \sum_{j=i}^{M} H_j \tag{12}$$

Where F_i, $\sum_{j=i}^{M} H_j$ and η are the same as above Eqs.(8), DH_i is the decreased water head when the current *i*-th station supplied water.

Due to the decrease of water head DH_i caused by the water supply of *i*-th reservoir, the additional energy of cascade hydropower system will be decreased in the following two parts. The first decreased water energy ΔE_w is caused by the power generation of *i*-th hydropower station with the inflow W_i at current period. The second decreased water energy is caused by the sum of the available water in the upstream of *i*-th reservoir in the cascade hydropower system. The calculation formula can be expressed as follow:

$$\Delta E_w = 0.00272 \cdot \eta \cdot W_i \cdot DH_i \tag{13}$$

$$\Delta E_v = 0.00272 \cdot \eta \cdot \sum_{j=1}^{i-1} V_j \cdot DH_i \tag{14}$$

Therefore, the decreased energy of cascade hydropower system at the end of the period when *i*-th reservoir supplies unit energy is:

$$K_i = \left(\Delta E_w + \Delta E_v\right) / \Delta E_x = \left(W_i + \sum_{j=1}^{i-1} V_j\right) / \left(F_i \cdot \sum_{j=i}^{M} H_j\right) \tag{15}$$

It can be seen from the calculation method of *K* value that reservoirs with small *K* value in supply period supply water first, namely, the smaller the K value of the same energy supplied by reservoirs, the less the total energy of cascade hydropower system decreases.

By comparing equations (11) and (15), it can be seen that the two can be uniformly expressed as:

$$K = \left(W + \sum V\right) / \left(F \cdot \sum H\right) \tag{16}$$

The *K* in equation (16) is called the discriminant coefficient or discriminant. The *K* value can also be used for parallel hydropower system. The conclusion is similar to the above, except that the value of $\sum V$ in equation (16) is set as 0 and value of $\sum H$ becomes *H*.

Discriminant physical meaning is clear, simple and practical. It has been widely attention in theoretical research and engineering application. In practical application, based on the current power station inflow *W*, the sum of the available water $\sum V$ in the upstream of the current reservoir in the cascade hydropower system, the current reservoir area *F* and the sum of power generation heads of current power station and its downstream cascade, discriminant coefficient *K* can be calculated for each station, to determine the reasonable water storage and supply order of each reservoir in the hydropower systems.

(3) The relative water storage rate of cascade reservoirs

The physical significance of relative storage rate is to measure the water volume difference between two reservoirs and can be used to control the water in each reservoir. The aim of proposed this is from the perspective of control the existing water difference for each reservoir at current period, when given certain value of relative water storage rate, it can prevent two reservoir water difference too big and avoid part of the reservoir is stored too full in the storage period or is emptied water in the supply period and lost the adjustment ability of the reservoir. Thus, to deal with the extreme situation, a small amount of reservoir volume is reserved to prevent the excessive inflow that resulting in the abandonment of water in the future storage period, and a certain amount of water is left to prevent the insufficient inflow that cannot provide firm energy with the deep damage in the future supply period. The calculation formula of the relative storage rate of a reservoir at the current period is as follows:

$$r_i = \left(V_i - V_i^{dead}\right) \Big/ \left(V_i^{\max} - V_i^{dead}\right) \tag{17}$$

$$R_i^j = \left|r_j - r_i\right| \le \delta \tag{18}$$

Where r_i is the water storage rate of *i-th* reservoir at a certain period, the value ranges from 0 to 1, V_i , V_i^{dead} and $V_i^{\max}$ are the initial reservoir volume of the current period, the minimum and maximum reservoir volume of *i-th* reservoir, R_i^j is the absolute value ($j \neq i$) of the difference in water storage rate between *j-th* reservoir and *i-th* reservoir , the value ranges from 0 to 1, δ is the control value of the given relative storage rate.

2.3 ***Solution method based on the coupling of water storage rate and discrimination coefficient method***

First, the total output N_q of cascade hydropower system at the current period is calculated and compared with the given total output N_s of cascade hydropower system at the current period.

(1) When $N_q > N_s$, the cascade hydropower system should store water. According to the discriminant coefficient method, the *K* values of each reservoir in the cascade are calculated and sorted from large to small. Assuming that the *K* of *i-th* reservoir is the largest, it is determined by the discriminant coefficient method that the water is first stored in *i-th* reservoir, and then on the basis of the relative water storage rate of *i-th* reservoir, the relative water storage rate R_i^j of *j-th* other reservoir to *i-th* reservoir in the cascade is calculated. Given the control value of relative water storage rate δ in a certain allowable range, the relative water storage rate R_i^j of *j-th* other reservoir to *i-th* reservoir can be divided into the following two conditions:

① If $\forall R_i^j \le \delta$, that is, the relative water storage rate R_i^j of all other reservoir to *i-th* reservoir in the cascade system is within control value δ of the relative water storage rate, then the order of water storage of each reservoir in the cascade hydropower system at current period is determined directly by the discriminant coefficient method.

② If $\exists R_i^j > \delta$, that is, in the cascade system existing relative water storage rate R_i^j of some reservoir to *i-th* reservoir is beyond control values δ of relative water storage rate, then the relative water storage rate *R* of meeting this conditions are sorted from large to small as the order of each reservoir stored water. The reservoir with the biggest value *R* will generate power with partial inflow and store partial inflow, while other reservoirs will generate power with total inflow. The amount of water stored depends on the total output is equal to given N_s of the cascade hydropower system. If the total output is still greater than N_s when the current reservoir is stored to the maximum water level, then the water shall be stored in the order of value *R* from large to small, until the total output is equal to N_s or all reservoirs with value *R* greater than δ are stored full. If the total output is still greater than N_s, the remaining reservoirs are then stored in the order of the discriminant coefficient *K* from large to small as the order of remaining reservoirs stored water, until the total output is equal to N_s or all the reservoirs are stored to the maximum water level.

(2) When $N_q < N_s$, the cascade hydropower system should supply water. According to the discriminant coefficient method, the *K* values of each reservoir in the cascade are calculated and sorted from small to large. Assuming that the *K* of *i-th* reservoir is the smallest, it is determined by the discriminant coefficient method that the water is first supplied in *i-th* reservoir, and then on the basis of the relative water storage rate of *i-th* reservoir, the relative water storage rate R_i^j of *j-th* other reservoir to *i-th* reservoir in the cascade is calculated. Given the control value of relative water storage rate δ in a certain allowable range, the relative water storage rate R_i^j of *j-th* other reservoir to *i-th* reservoir can be divided into the following two conditions:

① If $\forall R_i^j \le \delta$, the order of water supplied of each reservoir in the cascade hydropower system at current period is determined directly by the discriminant coefficient method.

② If $\exists R_i^j > \delta$, the relative water storage rate *R* of meeting this conditions are sorted from large to small as the order of each reservoir supplied water. The reservoir with the biggest value *R* will generate power with total inflow and partial supplied water of reservoir, while other reservoirs will generate power with total inflow. The amount of water supplied depends on the total output is equal to given N_s of the cascade hydropower system. If the total output is still less than N_s when the current reservoir is supplied to the minimum water level, then the water shall be supplied in the order of value *R* from large to small, until the total output is equal to N_s or all reservoirs with value *R* greater than δ are supplied empty. If the total output is still less than N_s, the remaining reservoirs are then supplied in the order of the discriminant coefficient *K* from small to large as the order of remaining reservoirs supplied water, until the total output is equal to N_s or all the reservoirs are supplied to the maximum water level.

(3) When $N_q = N_s$, the cascade hydropower system neither store water nor supply water. All cascade power stations generate power with total inflow. The sum of the outputs N_q of each power station is exactly equal to N_s.

Finally, after the calculation of the whole operation period, the optimal output distribution scheme of cascade hydropower system and the operation process of each cascade power station are obtained. The cascade hydropower system is operated in the optimal order of water storage and supply aiming at both cascade generation efficiency and water volume control.

3 CASCADE JOINT OPERATION BASED ON ENERGY STORAGE OPERATION CHART

3.1 *Drawing of cascade energy storage operation chart*

The drawing form of the cascade energy storage operation chart is obtained from the envelope of the hydropower calculation in several typical years from a long series of historical runoff data. There are three basic operation lines: the maximum energy storage line, the upper and lower basic operation lines. The operation chart is divided into three areas: firm power area, increased power area and reduced power area. According to the actual demand the operation chart also can add a number of increase or decrease operation line, the drawing method of each operation line is as follows:

(1) The maximum energy storage line

The maximum cascade energy storage is the sum of the energy storage when each reservoir is stored full. According to the maximum water level of each reservoir at each period, the corresponding energy storage of each reservoir is calculated, and the total cascade energy storage of each period can be obtained by adding them together. Then, the cascade maximum energy storage line is drawn by connecting the points of the total energy storage of each period with a line.

(2) The upper and lower basic operation line

The typical year is selected under the following conditions: in the historical runoff data, the selected inflow is similar to the water supply that cascade hydropower system is operated according to total firm power, but the inflow yearly distribution is different for several years. The drawing of the upper and the lower basic operation line: for each typical year, starting from the minimum water level at the end of water supply period, energy storage operation are carried out at each period according to the total firm power, namely the cascade load distribution method will be adopted for the total firm power distributing to each power plant. According to the distribution power, the power plant reverses to hydropower calculation to nearby the minimum water level at beginning of the storage period. It can obtain the beginning water level of each period and its corresponding cascade energy for each plant, and the total energy storage at each period can be obtained by adding them together. The upper envelope line is taken as the upper basic operation line and the lower envelope line is taken as the lower basic operation line of the cascade energy storage operation chart.

(3) The increase and decrease operation line

Based on the total energy storage of the upper and lower basic operation line, the typical runoff process of each period corresponding to the upper and lower basic operation line is obtained by hydropower calculation according to the total firm power. According to this typical runoff process, the increase and decrease operation line are drawn by hydropower calculation of the same power with different power times ratio. Specific realization process: according to the typical runoff process obtained by the total energy storage of the upper basic operation line, the total increased output and the output distribution method of the discriminant coefficient, the increase operation line is drawn by hydropower calculation of reverse with the same increased power, distributed by the discriminant coefficient. According to the typical runoff process obtained by the total energy storage of the lower basic operation line, the total decreased output and the output distribution method of the discriminant coefficient, the decrease operation line is drawn by hydropower calculation of reverse with the same decreased power, distributed by the discriminant coefficient.

3.2 *Application rules of cascade energy storage operation chart*

When the cascade energy storage operation chart guides the actual operation of the cascade hydropower system, it usually operates in the following way:

(1) When the total energy storage of the cascade hydropower system is located in the total firm power area between the upper and lower basic operation line of the cascade energy storage operation chart, the cascade hydropower system is operated with the total firm power.

(2) When the total energy storage of the cascade hydropower system is located in the increased power area above the upper basic operation line of the cascade energy storage operation chart, the cascade hydropower system is operated with the total output indicated in the increased operation line.

(3) When the total energy storage of the cascade hydropower system is located in the decreased power area below the lower basic operation line of the cascade energy storage operation chart, the cascade hydropower system is operated with the total output indicated in the decreased operation line.

3.3 *The simulation of energy storage operation chart based on cascade load distribution method*

The rationality of the cascade energy storage operation chart can be calculated and verified by the simulation operation according to the actual long-term historical runoff data, and analyzed according to several evaluation indicators of the simulation operation. The total output of the hydropower system can be obtained by using the cascade energy storage operation chart, and combining with the cascade load distribution method, the specific steps of the cascade simulation operation are as follows:

(1) According to the water level at the beginning of current period and basic parameters of each reservoir, the total energy storage of the cascade hydropower system is calculated, and the total output of the cascade hydropower system at the current period is obtained according to the application rules of the cascade energy storage operation chart.

(2) According to the given total output of cascade hydropower system at current period, combined with the corresponding cascade load distribution method in Section 2.2, the output of each hydropower station at current period is obtained to guide the operation of each single reservoir, and the water level at the end of current period of each reservoir and the total energy storage of the cascade hydropower system are obtained.

(3) To judge whether the state at the end of current period of each reservoir meets the constraint conditions. If the constraint conditions are satisfied, each reservoir at this period will operate with the given output process. If the constraint conditions are not satisfied, the output of the reservoir at current period shall be adjusted:

① If the water level at the end of current period is higher than the maximum water level, it means that the given output of the reservoir is too small, then the maximum water level of the reservoir is taken as the water level at the end of current period, and the output of the reservoir at current period is determined by hydropower calculation.

② If the water level at the end of current period is lower than the minimum water level, it means that the given output of the reservoir is too large, then the minimum water level of the reservoir is taken as the water level at the end of current period, and the output of the reservoir at current period is determined by hydropower calculation.

4 CASE STUDY

4.1 *Basic data of cascade hydropower station*

The YuanShui River Basin is the second largest river in Hunan Province, China, with a total length of about 1,000 km. It has a natural fall of about 1,400 meters, and covering an area of about 89,100 km^2. In this paper, only four hydropower stations of SanBanxi, BaiShi, TuoKou and WuQiangxi with above seasonal storage are selected as the research objects for the joint operation of cascade hydropower system. The basic data of this four hydropower stations in the main stream of YuanShui River Basin is shown in table 1.

Table 1.The basic data of four hydropower stations in the main stream of YuanShui River Basin

Plant	Full Supply Level(m)	Minimum Operation Level(m)	Live Storage(Million m^3)	Installed Capacity(MW)	Firm Power(MW)	Design flow(m^3/s)	Regulation Ability
SanBanxi	475	425	2,616	1,000.0	234	900	Carry-over Storage
BaiShi	300	294	172	420.0	89.7	450	Seasonal Storage
TuoKou	250	235	615	830.0	129.3	1742	Incomplete Annual Storage
WuQiangxi	108	90	2,020	1,200.0	255	3,35	Seasonal Storage

4.2 *Results*

4.2.1 *The cascade energy storage operation chart*

According to the drawing method of above Section 3.1, the cascade energy storage operation chart in the main stream of YuanShui River Basin is shown in Figure 1.

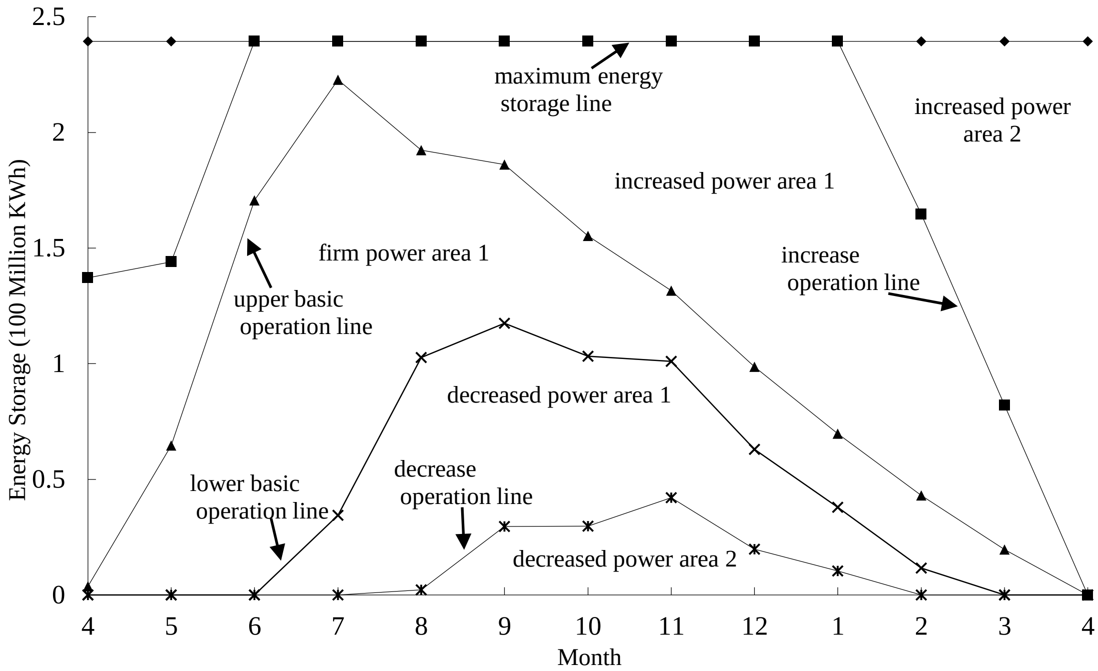

Figure 1.The cascade energy storage operation chart

4.2.2 ***Simulation results***

After drawing of the cascade storage operation chart, the total output of the cascade is determined in the cascade storage operation chart according to the water level at beginning of current period of each reservoir, and then the total output is distributed reasonably to each hydropower station for actual operation. The following two load distribution schemes are compared and analyzed: Scheme 1, the discriminant coefficient method of commonly used; Scheme 2, the method of coupling water storage rate and discriminant coefficient method is proposed in this paper.

In Scheme 2, according to the existing hydrological data with a series of simulation, the different control values δ of relative water storage rate are selected to obtain different operation schemes. The annual average power generation, reliability requirement of power generation and annual average surplus water are taken as the evaluation indicators of the each operation scheme, and 5 non-inferior solution schemes and Scheme 1 are selected for comparison, as shown in table 2.

Table 2. Evaluation indexes of non-inferior schemes in Scheme2 and Scheme 1

Items	Control values of relative water storage rate	Annual average power generation of cascade(100 million kWh)	Reliability requirement of power generation	Annual average surplus water(100 million m^3)
Scheme 1	−	105.64	91.32%	31.56
	0.57	104.56	92.53%	32.30
	0.80	105.66	91.84%	29.79
Scheme 2	0.83	105.74	92.19%	29.75
	0.87	105.88	92.36%	29.95
	0.95	105.84	92.36%	30.58

When the cascade load distribution method of coupling water storage rate and discriminant coefficient method is adopted, the load distribution method cannot uniquely determine an optimal operation scheme because of the control values choice of the relative water storage rate, the decision makers should make a careful balance between cascade power generation, cascade surplus water and reliability requirement of power generation according to the different target demand.

5 CONCLUSIONS

By comparing and analyzing the operation results of two different cascade load distribution methods, from the perspective of comprehensive consideration of cascade power generation benefit, cascade surplus water and reliability requirement of power generation, the results show that the simulation operation results of the energy storage operation chart based on the coupling distribution method of water storage rate and discrimination coefficient proposed in this paper, can improve the power generation benefits of cascade or the reliability requirement of power generation, according to the reasonable selection of the control value of the relative storage rate. The reason is that this method uses a small head loss for water control of each reservoir, to reduce water abandoned of downstream reservoir because the downstream reservoir is stored full too early during the wet season. At the same time, to increase water volume of upstream reservoir for providing a certain reliability requirement of power generation of cascade hydropower stations during the dry season, so as to make up for the deficiency of the discriminant coefficient method of commonly used. Therefore, simulation operation results verify the rationality and practicability of this method proposed in this paper.

REFERENCES

Ruey-Hsun, L. & Yuan-Yih, H. 1995. A hybrid artificial neural network—differential dynamic programming approach for short-term hydro scheduling. *Electric Power Systems Research* 33:77-86.

Shyh-Jier, H. 1998. Hydroelectric generation scheduling—an application of genetic-embedded fuzzy system approach. *Electric Power Systems Research* 48: 65-72.

Kumar, A. R. S. & Goyal, M. et al. 2013. Application of ANN, fuzzy logic and decision tree algorithms for the development of reservoir operating rules. *Water Resources Management* 27(3): 911 - 925.

Liu, X. & Guo, S. et al. 2009. Study on the optimal operating rules for cascade hydropower stations based on output allocation model. *Journal of Hydroelectric Engineering* 28(3):26-31.

Ji, C. & Jiang, Z. et al. 2014. Optimization of cascade total output dispatching figure in Li Xianjiang basin. *Journal of Hydraulic Engineering* 45(2):197-203.

Xie, X. 2005. Reservoir operation to meet load requirements. *Water Power* 31(9): 75-80.

Bellman, R.E & Zadeh, L.A. 1970. Decision making in a fuzzy environment. *Management Science* 17(B): 141-164.