Research on Real-time Intelligent Load Control Technology among Giant Hydropower Station Group under High-intensity Peak-load and Frequency Regulation Demand

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Abstract: The paper conducts an in-depth study on the real-time dispatching involved in joint operation among giant cascade hydropower stations with high-intensity peak-load and frequency regulation demand, and proposes an intelligent load control technology for cascade hydropower stations in the coordination mode of station and power grid. Aiming to water level safety control of runoff power stations and rapid response to load regulation requirements of the power grid, taking 10 types of constraints such as output, water volume and flow rate into consideration, a model cluster is established through the layered control principle to realize real-time intelligent load allocation and economic operation among Pubugou, Shenxigou and Zhentouba stations. Dadu River has become the first large-scale river basin in China to realize “one-key dispatch” of multiple stations, and has achieved good demonstration effect.

1 Introduction

Clean energy is abundant in Sichuan province. By the end of 2017, the total installed capacity based on clean energy has reached 83,730,000kW in Sichuan, accounting for 86.1% of the total installed capacity of Sichuan province. Affected by uncertainty of flow and wind, as well as poor regulation performance of most hydropower stations in Sichuan, load curves of most peak-load and frequency regulation hydropower stations in Sichuan is featured by big changes and frequent adjustments, with strong randomness and uncertainty. Especially after Chongqing-Hubei back-to-back flexible DC project put into operation, it is expected that the southwest power grid will be formally interconnected asynchronously with its external power grid in early 2019, scope of its synchronous grid will beonl about 1/6 of the original Southwest China Power Grid -Central China Power Grid -North China Power Grid. As a result, the structural contradiction of power supply of Southwest Power Grid may become more prominent, which may propose higher requirements for response speed of load regulation of peak-load and frequency regulation units.

The three hydropower stations (Pubugou, Shenxigou, Zhentouba) cascaded on the middle and lower reaches of Dadu River have total installed capacity of 4,980,000kW, the three hydropower stations are the main peak-load and frequency regulation forces of Sichuan Power Grid. In actual operation, because of the small reservoir capacity of Shenxigou and Zhentouba stations, their water levels are affected greatly by load of the upstream Pubugou. Traditional station AGC, which cannot control water levels harmoniously and economically, has to be suspended, only passively accepting "fixed load" command issued by power grid control center, resulting in large fluctuations in water levels, abandoned water, reservoir draining-out of the two reservoirs, etc., seriously affecting the safe and economic operation of cascade power stations.

The issue of real-time optimal load distribution between cascade hydropower stations in a river basin has always been a study hotspot in the hydropower energy optimization and operation. In view of the high-intensity peak-load and frequency regulation demand due to the characteristics of Sichuan power grid, this paper proposes a kind of intelligent load control method for cascade hydropower stations aiming at coordination of stations and power grid, and hence realizes the real-time intelligent load distribution and economic operation among cascades of Pubugou, Shenxigou and Zhentouba stations on the basis of fast respond to power grid demand.

2 Status Quo and Technical Difficulties

Real-time dispatching of cascade hydropower stations is closely related to not only power system, but also water conditions of the reservoirs. It is necessary to consider the constraints of power grid, reservoir and units, as well as economic operation in each power station. This is a typical discontinuous multi-dimensional constraint problem. The existing joint optimized dispatching technology mostly aiming at dispatching optimization by optimization of power generation plan, however, the demand for frequency stability of power grid cannot be
satisfied only by optimization of power generation plan due to its deviation in actual operation. For real-time automatic generation control, most hydropower stations are controlled by AGC on cascade stations. Although AGC running on cascade stations, or economic dispatching control EDC, is attempts applied in cascade hydropower stations like Three Gorges–Gezhouba cascade, Qingjiang cascade, Wujiang cascade, Yalongjiang River downstream cascade etc. [1-12] however, most are still in a theoretical exploration stage, with distribution strategy mainly aiming at minimum energy consumption or stationary water level taking the upstream/downstream flow into consideration. There is not yet mathematical models or optimization methods with rigorous theory, universality and practicability. Therefore, there is no precedent of automatic model for total-load dispatch between cascade hydropower stations in large basin put into operation in China.

3 Analysis of Influence Factors of Dadu River

3.1 Weak Overall Regulation Performance in Reservoirs of Dadu River Basin

A reservoir’s regulation performance determines its bearing capacity to inflow changes. According to regulation coefficient β of reservoir capacity, a reservoir’s regulation performance can be classified into different types such as daily regulation, weekly regulation, monthly regulation, quarterly regulation, yearly regulation and multi-year regulation etc. In case when β<2%, the reservoir belongs to the type of no regulation, when β is between 2% and 8%, quarterly regulation, when β is between 8% and 30%, yearly regulation, of which 8%-20%, incomplete yearly regulation, 20%-30%, complete yearly regulation, when β>30%, multi-year regulation [13]. Of the three stations mentioned above, only Pubugou has incomplete yearly reservoir regulation ability, while Shenxigou and Zhentouba reservoirs are just runoff, with poor adjustment capacity.

Table 1 Pubugou, Shenxigou and Zhentouba reservoir adjustment characteristics

| Reservoir | Pubugou | Shenxigou | Zhentouba |
|-----------|---------|-----------|-----------|
| Regulation capacity /million m³ | 3826 | 8.14 | 12.3 |
| Regulation coefficient /% | 9.70 | 0.02 | 0.03 |

3.2 Complex and Changeable Electric Power Market Environment in Sichuan Province

In an ideal state, if real-time power generation follows the 96-point plan (15 mins for each, 24 hours for 96-points) which is made to match water consumption of Pubugou and other cascade hydropower stations below, fluctuation of water level, abandoned water, draining-out of reservoir caused by water consumption mismatch of different cascades can be greatly reduced. However, the tough power market environment in Sichuan causes three major problems about the joint optimization and dispatching of cascade stations: (1) It is difficult to generate matchly between different cascades in an overall surplus electric market environment with severe generation limit and low load rate, esp. in flood season. (2) Pubugou Power Station shoulders the main task of peak-load and frequency regulation in Sichuan power grid. The provincial dispatching center regulates its output according to system tide by grid AGC, resulting in a frequent and sharply fluctuated regulation of the output during one day, as a result, the load of downstream cascade power station cannot keep pace with the upstream Pubugou Station in time. (3) Sichuan electric power market policy changes frequently, and new marketing models such as day-ahead trading and deviation assessment etc. emerge continuously, especially in the current of power surplus state, little effect can be obtained through matching power generation load of each station to control outflow rate. The typical daily load statistics in flood season of 2017 shows that the deviation between real load and planned load of the three stations (Pubugou, Shenxigou, Zhentouba) was generally significant, of which Pubugou Station showed the biggest impact by AGC of provincial control center. The deviation between the real load and the planned load accounts for 26.55% of the planned value.

Table 2 Comparison of load plan and actual generating output of Pubugou, Shenxigou and Zhentouba stations of a typical day in flood season

| Reservoir | Pubugou | Shenxigou | Zhentouba |
|-----------|---------|-----------|-----------|
| Average value of deviation between real load and planned load (δ/10,000kW) | 44.40 | 5.80 | 5.97 |
| Average value of planned load (β/10,000 kW) | 167.20 | 40.49 | 40.98 |
| Deviation ratio (δ/β/%) | 26.55 | 14.32 | 14.74 |

4 Overall Technical Framework

Under the current architecture of automatic generation control (AGC) of power system in China, real-time load distribution of cascade hydropower stations should be deployed between power grid AGC and power stations AGC to realize the economic dispatching control of cascade hydropower station through coordinated operation of power grid, centralized control center and power stations and the premise of power system safety. The real-time intelligent load dispatch function of cascade hydropower stations can be either embedded in the power grid dispatching center, namely, the power grid dispatch center.
grid real-time intelligent load distribution system of cascade hydropower stations, or bedeployedin the centralized control center of power stations, namely, the centralized control center real-time intelligent load distribution system (See Fig. 1). The second mode is used in Dadu River. The whole idea is as follows:

Based on load demand or frequency deviation of power system, power grid dispatch center issues real-time generation sum-load command to the real-time intelligent load distribution system of cascade hydropower stations (Pubugou, Shexigou and Zhentouba). While monitoring operating conditions of each station AGC, the real-time intelligent load distribution system of cascade hydropower stations receives real-time load commands from power grid AGC, distributes the load among the three power stations, and sends the load distribution results to each power station AGC which is responsible for load distribution among units in the station, and returning the regulation results.

Due to unavoidable deviations in factors like predicted water level and minimum discharge flow of stations. The economical efficiency is embodied as follows: no abandoned water among the cascades, water consumption rate in the basin is optimal, number and times of units involved in regulation areas less as possible to reduce wear and tear of units, etc.

Therefore, the real-time load control is divided into two categories: command mode and non-command mode. In command mode, when power grid AGC issues load regulation command, the load distribution system automatically matches the fast regulation model to ensure the shortest time required to complete load regulation command of power grid with all power stations involved according to “the fastest speed of load regulation” model, hence to meet the demand of peak-load and frequency regulation of the power system. After the total load is regulated in place, on the premise of ensuring relative stability of total load, load of each station is redistributed in such a manner that is beneficial to economic operation of hydropower stations through forward and reverse simultaneous regulation and load transference between stations, so as to ensure the efficient utilization of water energy.

In non-command model, based on deviations between model calculation result and actual dispatching process, operational water level zone is divided into high zone, acceptable zone and dead zone. When water level enters the high zone or dead zone and shows no tendency of returning to acceptable zone, a model called abnormal operating zone with higher/lower water level; if it falls into Z_{z,down} or Z_{z,up}, it is deemed to have entered anomalous operating zone with higher/lower water level; if it falls into Z_{z,dead} or Z_{z,impounded}, it is deemed to have entered anomalous operating zone with higher/lower water level; if it falls into Z_{z,down} or Z_{z,up}, the reservoir is deemed operating in the acceptable water level zone. The principle for water level zoning control is shown in Fig. 2.
In joint regulation status of the three stations (Pubugou, Shenxigou, Zhentouba), the main task is to track the 500kV liaison line power flowlinking Sichuan and Chongqing grids. The three stationsare incorporated as a whole into the ancillary service management assessment of grid-connected power plants. The main assessment indexesinclude regulating precision and the regulating speed. Regulating precision requires that real-time load to enter a dead zone of the load command within specified time. The regulating speed is a cumulative value of ramping rate of all regulating units that are involved in AGC. The more units involved, the higher the requirements of regulating speed.

In response to such requirements of power grid, real-time load regulation of the three stations (Pubugou, Shenxigou and Zhentouba) optimizes to shorten the time the whole process of load command reception, distribution and execution needed to the greatest extent, and generalizes the results to shared steps of all models in order to shorten regulation time of every model. A fast regulation model based on the shortest regulation time is hence proposed. The objective function is as follows:

$$T = \min(t_r + t_c + \max \sum_{i=1}^{n}(t_{s,i} + t_{AGC,i} + t_{a,i}))$$

(1)

The main regulation processes are as follows:

a. Receive load command (time \(t_r\), required).

b. Calculate and distribute the load according to certain regulation model (time \(t_c\) required).

c. Send sub-load command results to each power station (time \(t_{s,i}\) required).

d. Calculate and distribute the sub-load by power station AGC among units \(n(t_{AGC,i})\) required).

e. Finish the regulation by power station AGC \((time_{a,i} \text{ required})\).

\(n\) is the quantity of cascaded power stations where load is distributed and regulated.

In the above formula, \(t_r, t_{s,i}, \text{ and } t_{AGC,i}\) are defined as time delay of channel and time delay of power station AGC calculation, \(t_c\) is sitio be optimized by abidiirectional successive approximation dynamic programming algorithm described below. Considering the difference in regulation performance of each power station, regulating speed is significantly different. In the calculation of load distribution, all power stations involved in the load distribution and regulation are theoretically required to complete their quotas in the same amount of time according to their regulating performance, so that it may take the shortest time for all power stations to jointly complete load regulation commands of the power grid, unless regulation boundary is confronted, such as vibration zone and adjustable range boundaries.

In this model, each power station is theoretically required to participate in load regulation every time, so problems-number of stations involved and regulating times are both large-can come with this model. Therefore, adaptive selection is adopted in engineering project by supplementarily use with small-load distribution model.

(2) Abnormal Water Level Model for Shenxigou and Zhentouba Stations

### 5.2 Models Composition

This paper mainly introduces fast regulation model, abnormal water level model and minimum water abandoning model. There will be no detailed description of other common models in this paper.

(1) Fast regulation model

![Fig. 2 Water level zoning control principle](image)

If water levels of Shenxigou and Zhentouba reservoirs are in acceptable zone, and there is water being discarded in at least one station among Pubugou, Shenxigou and Zhentouba power stations, then the minimum water abandoning model will be automatically initiated to reduce power loss caused by water discard.

The strategy of real-time load distribution among cascade hydropower stations (Pubugou, Shenxigou and Zhentouba) of Dadu River is shown in Fig. 3. Four types of which are optional economic dispatching models (max energy conservation, stable water level model, less regulation model, and balanced load model). In the non-command mode, certain models like abnormal water level models or minimum water abandoning model will be triggered automatically when certain requirements are met, of which the priority of former model is higher than the latter one.

![Fig. 3 The composition of real-time load distribution models](image)
Because of small reservoir capacity and poor regulation performance of Shenxigou Station and Zhentouba Station, this model aims to ensure the reservoir level of Shenxigou Station and Zhentouba Station to return to and keep operating near the median of its acceptable operating zone as long as possible after execution duration \( \tau \) (the time lag of the cascade flow) according to distribution results through load redistribution between stations.

\[
F = \min \left( \sum_{i,j,t} \left( Z_{i,\text{down}} + Z_{i,\text{up}} \right) \beta Z_{j,\text{up}} \right) (2)
\]

In the formula above, when the water level of Shenxigou is abnormal, \( \alpha = 1 \); when the water level of Zhentouba is abnormal, \( \beta = 1 \); \( Z_{s,t+\tau} \) is the corresponding reservoir level when Shenxigou is operating up to \( t + \tau \) time according to the distribution results at \( t \) time, and reservoir level can be calculated according to principle of water energy calculation and principle of water volume balance.

(3) Minimum Water Abandoning Model

In this model, load distribution is carried out based on minimizing the electricity loss caused by water abandoning of the three cascades by increasing load of those stations with surplus water and reducing load of stations without surplus water as far as possible. If every cascade power station is abandoning water, then load will be distributed in such a manner to minimize the electricity loss caused by surplus water.

\[
F = m \max \sum_{i,t} Q_{i,t} (3)
\]

In the formula above, \( Q_{i,t} \) is the average electricity loss caused by surplus water within \( t \) time of the NO. power station; \( n \) is the quantity of cascade power stations involved in load distribution.

6 Solution Algorithms

At present, solution algorithms commonly used for load distribution are traditional classical algorithms, represented by micro-increaseratemethod, dynamic programming (DP) and their improved algorithms, and modern bionics algorithms, represented by genetic algorithm (GA) and ant colony algorithm, etc. Because most of the latter ones have the problem of precocious convergence, so they are commonly used in the study stage. The former ones are strict in theory and can be absolutely converged in global optimal solution, however, the calculating amount will present a geometric growth with the increase of number of time periods. It may result in a too long solving time [14-20]. After receiving commands from the power grid, the distribution schemes of load commands among the cascade hydropower stations should be in real time. Every single calculation is required to be completed within 1 second.

For this purpose, “dynamic programming algorithm of bi-directional successive approximation” is adopted in this paper according to the characteristics that the initial state (the active load to be distributed is \( P_{\text{s+t}} \)) and the termination state (the active load to be distributed is zero) of the inter-station load distribution among the cascade hydropower stations are given in advance. Forward and reverse resolution can be carried out simultaneously by single machine multithreading or double machine multithreading according to computer software multithreading technology or distributed parallel computing technology. In theory, the speed for solving the problem can be almost doubled. The process flow of the “coupling efficient algorithm of bi-directional successive approximation” adopted in the paper is shown in Fig. 4.

7 Results and Analysis of Examples
Take a certain kind of operating condition as an example. 5 units in operation in Pubugou station within vibration zone as a whole and water level 825.7m; 4 units are in operation in Shenzixiogou station, the vibration zone in the whole plant is 20 ~ 85MW with water level 657m; 3 units are in operation in Zhentouba station with vibration area 15 ~ 90MW as a whole and water level 621m. Maximum energy conservation model has been selected as the economic operation strategy.

If the load change, increase or decrease, needed to be regulated is less than 50MW, then small load model will be automatically initiated and Pubugou station will undertake independently the load change.

Otherwise, the system will firstly adopt fast regulation model to regulate the total load to dead zone of the target load, later it will transfer automatically to maximum energy conservation mode, reducing the load value of Pubugou at a constant speed while increasing the load of Shenzixiogou and Zhentouba Station at the same speed, in order to store more water in reservoir of Pubugou.

For example, a command with total load of the three stations increase from 3,000MW to 3,200MW issued from the grid. The target load and the time needed for regulation in each station under different strategy models are shown in Table 3.

| Power Station | Initial Load /MW | Max energy conservation | Less regulation | Stable water level | Fast regulation |
|---------------|------------------|-------------------------|-----------------|-------------------|-----------------|
|               | Target load /MW  | Regulation time/min     | Target load /MW | Regulation time/min | Target load /MW | Regulation time/min |
| Pubugou       | 2180             | 0                       | 2380            | 1.34              | 2340            | 1.07              | 2291.1           | 0.75             |
| Shenzixiogou  | 420              | 1.67                    | 420             | 0                 | 460             | 0.67              | 464.4            | 0.75             |
| Zhentouba     | 400              | 1.67                    | 400             | 0                 | 400             | 0                 | 444.5            | 0.75             |
| Total         | 3000             | 1.67                    | 3200            | 1.34              | 3200            | 1.07              | 3200             | 0.75             |

After the first round of load regulation, target load values of the three stations gradually transits to distribution value of maximum energy conservation model, namely, the target load value of Pubugou is segmentedly reduced to 2,180MW to ensure that time needed for load reduction is almost identical to the time needed for load increase of Shenzixiogou and Zhentouba; the target load value is increased to 520MW in Shenzixiogou, and 500MW in Zhentouba. The result of the simulated operation for 1 hour shows average water consumption rate of the three cascades is 5.22m³/kWh under the maximum energy conservation model, and water consumption is 3.55% lower than fast regulation model, the saved water can generate additional electricity of about 110,000kWh.

It can be seen that cascade stations can respond in the shortest time in fast regulation model with total load regulated in place quickly. Through twice load distribution, the three stations can operate in an economical and reasonable load zone, thus to balance the speediness and economical efficiency of load regulation.

8 Conclusion

Taking water level safety control in run-off power stations and rapid response to load regulation command as hard constraints of Dadu River, the paper incorporates 10 kinds of constraints (output balance, water balance, flow balance, water level, generation flow, outflow, active adjustable range, amplitude output variation, avoidance of vibration area, inter-station load transfer limit), constructs 2 kinds of safety dispatching models (fast regulation and abnormal water level) and 5 kinds of economic dispatching models (minimum water outflow, maximum energy conservation, stable water level, less regulation and balanced load); and establishes a model cluster according to the principle of layered control, to realize intelligent load regulation required by high-intensity peak-load and frequency regulation of power system. Taking the year 2017 as an example, the three stations have significantly reduced manual load regulation by more than 30,000 times, and have increased the power generation output by 120 million kWh in dry season, compared with the year 2106. However, from the perspective of practical experience, the following problems need further study.

(1) The economic operation and the real-time load intelligent regulation of cascade hydropower stations need to couple with multi-dimensional factors. Contradictions and conflicts exist between the power system’s dependence on fast peak-load and frequency regulation capability and self-optimization of the cascade stations in adrainage basin, so further study is needed for real-time load optimization and regulation technologies under Multi-Factor Game Theory.

(2) Some supporting technologies related to real-time
intelligent load regulation of cascade power stations need to be improved, for instance, short-term runoff forecasting technology, algorithm for load distribution and coordination control technology between primary and secondary frequency regulation.

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