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 anintelligent 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 regulationperformance of mosthydropower stations in Sichuan, load curves of most peak-load and frequency regulation hydropower stationsin Sichuan is featured by big changes and frequent adjustments, withstrong randomness and uncertainty. Especiallyafter Chongqing-Hubei back-to-back flexible DCproject put into operation, it is expected that the southwest power grid will be formally interconnected asynchronously with its external power grid in early 2019, scale of its synchronous grid will beonly 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 ofload regulation ofpeak-load and frequency regulation units.

The three hydropower stations (Pubugou, Shenxigou, Zhentouba)cascadedon the middle and lower reaches of Dadu River havea total installed capacity of 4,980,000kW,the threehydropower stations arethe main peak-load and frequency regulation forcesof Sichuan Power Grid. In actual operation, because of the smallthe reservoir capacity of Shenxigou and Zhentouba stations, theirwater levelsare affected greatly by load of the upstream Pubugou.Traditional station AGC,whichcan not control water levels harmoniously and economically, has to be suspended, only passively accepting "fixed load"commandsissued bypower grid conctrol center, resulting in large fluctuations in water levels, abandoned water , reservoir draining-outof the two reservoirs, etc., seriously affecting the safe and economic operation of cascade power stations.

The issue of real-time optimalloaddistributionbetweencascade hydropower stations in a river basin hasalways been a study hotspot in the hydropower energy optimization and operation. In view of the high-intensity peak-load and frequency regulation demand due tothe characteristics of Sichuan power grid, this paper proposes a kind of intelligent load control method for cascade hydropower stations aiming atcoordination 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 relatedto not onlypower system, but also water conditionsof the reservoirs. It is necessary to consider the constraints of power grid, reservoir andunits,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 atdispatching optimization by optimization of power generation plan, however, the demand for frequency stability of power gridcannot be satisfied only by optimization of power generation plan due to its deviation in acutal operation. For real-time automatic generation control, most hydropower stations are controlled by AGC running on single station. Although AGC running on cascade stations, or economic dispatching control EDC,is attemptly appliedin 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, withdistribution strategy mainly aiming atminimum energy consumption or stationary water level takingthe upstream/downstream flow into consideration. There is not yet mathematical models and optimization methods with rigorous theory, universality and practicability. Therefore, there is no precedent of automatic model for total-loaddispatch between cascade hydropower stations in large basinsput into operation in China.

3 Analysis ofInfluence Factors of Dadu River

3.1 Weak Overall Regulation Performance in Reserviors of Dadu River Basin

A reservoir's regulation performance determines its bearing capacity to inflow changes. According to regulation coefficient β of reservoir capacity, areservoir'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 reservior 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]. Ofthe three stations mentioned above, only Pubugou has incomplete yearly reservior regulation ability, while Shenxigou and Zhentouba reserviors are just runoff, with poor adjustmentcapacity.

Table 1 Pubugou, Shenxigou and Zhentouba reservior adjustment characteristics

Reservior	Pubugou	Shenxigou	Zhentouba
Regulation capacity /million m^3	3826	8.14	12.3
Regulation coefficient /%	9.70	0.02	0.03

3.2 Complexand Changeable Electric Power Market Environment in Sichuan Province

In anideal 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 ofPubugou and other cascade hydropower stations below, fluctuation of water level, abandonedwater, draining-out ofreservoircaused by water consumption mismatch of different cascades can be greatly reduced. However, the toughpower 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 marketenvironment with severe generation limit and low load rate, esp. in flood season. (2) Pubugou Power Station shouldersthe main task of peak-load and frequency regulationin Sichuan power grid. The provincial dispatching center regulates its output according to system tide by gridAGC, resulting in a frequent and sharply fluctuated regulation of the output duringone 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 &day-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) wasgenerally significant, ofwhich Pubugou Station showed the biggest impactby AGC of provincial controlcenter. 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

	Pubugou	Shenxigou	Zhentouba
Averagevalue of deviation between real load and planned load (δ/10,000kW)	44.40	5.80	5.97
Averagevalue 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 stationsthrough coordinated operation ofpower grid, centralized control center and power stationson the premise of power system safety. The real-time intelligent load distribution function of cascade hydropower stations can be either embedded in the power grid dispatching center, namely, the power grid real-time intelligent load distribution system of cascade hydropower stations, or bedeployedin the centralized control center of power stations, namely, thecentralized control center real-time intelligent load distribution system(See Fig. 1). The second mode is usedinDadu River. The whole idea is as follows:

Based on load demand or frequency deviationof power system, power grid dispatching center issues real-time generation sum-load command to the real-time intelligent load distribution system of the cascade hydropower stations (Pubugou, Shenxigouand Zhentouba). While monitoring operating conditions of each station AGC, the real-time intelligent load distribution system of cascade hydropower stations receives real-timeload 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.

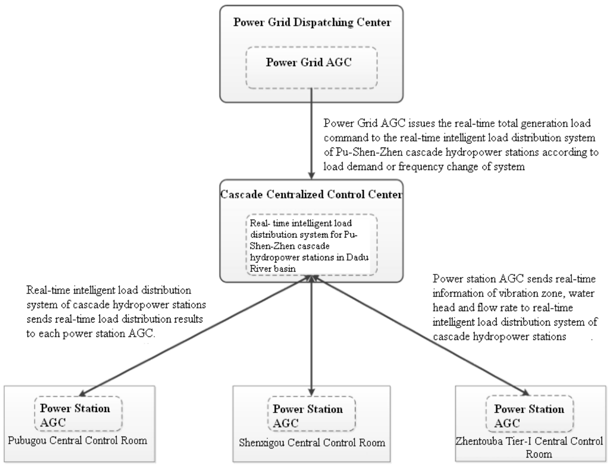

Fig. 1 Dispatching instruction relationship of load distribution in centralized control center

5 Overall Strategy and Models Composition

5.1 Overall Strategy

At present, the real-time load distribution model of cascade hydropower stations AGC at home and abroad is relatively simple, mainly relying on the model with minimum energy consumption, i.e.maximum energy storage, or stationary water level taking into the upstream and downstream flows for power generation [2-4]. However, both the two models have weaknesses: (1) The ramping rate of load regulation foreach cascade station is often different (quick or slow), resulting in a longer time spent on joint regulation by multiple power stations than by asingle station with faster speed, hence the demand forhigh-intensity peak-load and frequency regulation of power grid is difficult to be satisfied. (2) Due to unavoidable deviationsin factors likepredicted future flow and inaccurate water consumption rate adopted in calculation, accumulation of such deviationsmay cause water level to easily exceed the upper or lower limit after a long time operation of single model. As a result, stable operation cannot be guaranteed.

Safety takes precedence of economical efficiency in real-time dispatching of cascade hydropower stations. The safety is mainly embodied in two aspects as follows. (1)Respond to demand of peak-load and frequency regulation of power grid fast enough to guarantee itsfrequency stability; (2) Fulfulling the safety constraints about running water level and minimum discharge flow of stations. The economical efficiency is embodied as follows:noabandonedwater among the cascades, water consumption rate in the basin is optimal, number and times of units involved in regulationareas 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 aload regulation command, the load distributionsystem automatically matches the fast regulation model to ensure the shortest time required tocomplete 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 betweenstations, 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 showsno tendency of returning to accpetable zone, a model called abnormal water level model will be automatically matched and initiateload redistributionamong Pubugou, Shenxigou and Zhentouba stations to expeditereturningof the anomalous water level to its operating zoneas soon as possible, and the time-accumulated effect caused by calculation error will be offset as well. Specifically, a water level control range $Z_{z,down}\sim Z_{z,up}$ is set up between dead water level $Z_{z,dead}$ and normal impoundedwaterlevel$Z_{z,impounded}$ of arunoff power station (e.g. Zhentouba Station). When real-time water level $Z_{z,t}$ of Zhentouba reservoir satisfies $Z_{z,up}<Z_{z,t}\leq Z_{z,impounded}$ or $Z_{z,dead}\leq Z_{z,t}<Z_{z,down}$, it is deemed to have entered anomalous operating zone with higher/lower water level; If it falls into $Z_{z,down}\sim Z_{z,up}$, the reservior is deemed operating in the acceptablewater level zone. The principle for water level zoning control is shown in Fig. 2.

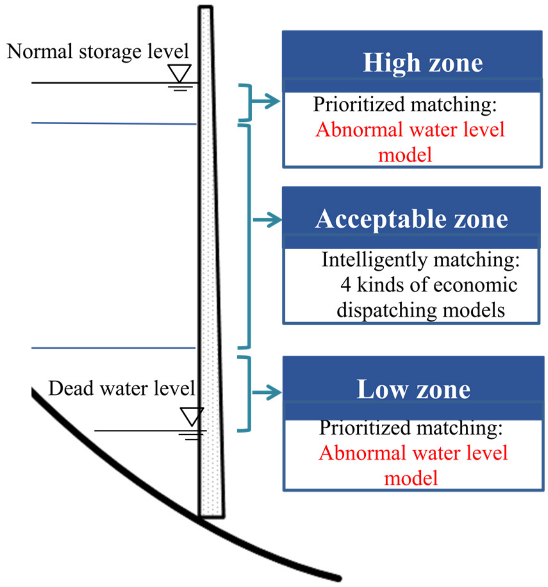

Fig. 2 Water level zoning control principle

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

The strategyof 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 modelslike abnormal water level modelor minimum water abandoning model will be triggered automatically when certain requirments are met, of which the priority of former model is higher than the latter one.

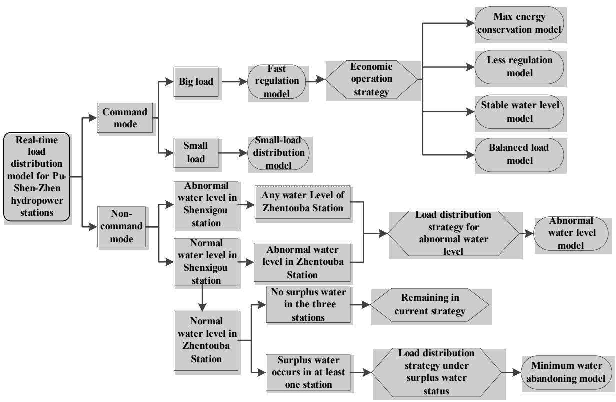

Fig. 3 The composition of real-time load distribution models

5.2 Models Composition

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

(1) Fast regulation model

In joint regulation status of the three stations (Pubugou, Shenxigou, Zhentouba), the main task is to track the 500kV liaison linepower flowlinking Sichuan and Chongqinggrids. The three stationsare incorporated as a whole into the ancillary service management assessmentof grid-connected power plants. The main assessment indexesinclude regulating precision and the regulating speed. Regulating precisionrequires that real-time load to enteradead zone of the loadcommand within specified time. The regulating speed is a cumulative value of ramping rate of all regulating units that areinvolvedin AGC. The more units involved, the higher the requirments of regulating speed.

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

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

The main regulation processes are as follows: a.Receive load command (timet_r,required).

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

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

d.Calculate anddistribute the sub-loadby power station AGC among units(time$t_{AGC,i}$) required).

e.Finish the regulation by power station AGC （time$t_{a,i}$ required）.

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

In the above formula, t_r, $t_{s,i}$, $t_{AGC,i}$ are defined as time delay of channel and time delay of power station AGC calculation, t_c is ois to be optimized by abi-directional successive approximation dynamic programming algorithm described below. Considering the difference in regulation performance of each power station, regulating speed is significantlydifferent. In the calculation of load distribution, all power stations involved in the load distribution and regulation are theoretically required to complete their quotas(inthe same direction) 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 rangeboundaries.

In this model, each power station is theoretically required to participate in load regulation every time, soproblems-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

Because of small reservoir capacity and poor regulation performance of Shenxigou Stationand Zhentouba Station, this model aims to ensure the reservoir level of ShenxigouStation and Zhentouba Station to return to and keep operating near the median of its acceptable operating zone as longas possible after execution duration τ (the time lag of the cascade flow) according to distribution results through load redistribution between stations.

$$F = \min\left(\alpha\left|Z_{s,t+\tau}-\frac{Z_{s,down}+Z_{s,up}}{2}\right|+\beta\left|Z_{z,t+\tau}-\frac{Z_{z,down}+Z_{z,up}}{2}\right|\right) \quad (2)$$

In the formula above, when the water level of Shenxigou is abnormal, α=1; when the water level of Zhentouba is abnormal, β=1; $Z_{s,t+\tau}$ is the corresponding reservoir level when Shenxigou is operatingup 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 outbased on minimizing the electricity loss caused by water abandoningof the three cascades by increaseing load of those stations with surplus water and reduceingload of stations without surplus water as far as possible. If every cascade power station is abandoningwater, then load will be distributed in such a manner to minimize the electricity loss caused by surplus water.

$$F = \min \sum_{i=1}^{n} Q_{i,t}^{qi} \quad (3)$$

In the formula above, $Q_{i,t}^{qi}$ is the average electricity loss caused by surplus water within t time of the NO. i 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 arestrict in theory and can be absolutely converged in global optimal solution, however, the calculating amountwill present a geometric growthwiththe increase of number of time periods. Itmay result in atoo 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 1second.

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_{set}) 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. Forwardandreversesolution 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.

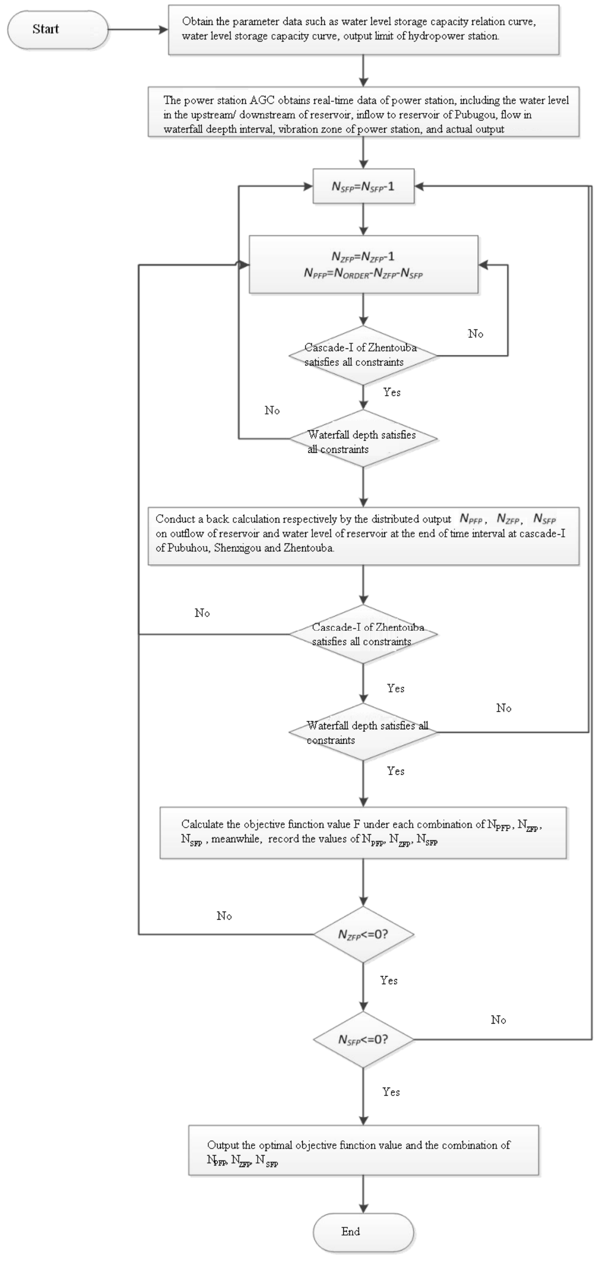

Fig. 4 Solution process of real-time load distribution among Pubugou, Shenxigou and Zhentouba three-station cascades

7 Results and Analysis of Examples

Take a certain kind of operating condition as an example. 5 units are in operation in Pubugou station withno vibration zone as a whole andwater level 825.7m; 4 units are in operationin Shenxigoustation, the vibration zonein the whole plant is 20 ~ 85MW with water level 657m; 3 units are in opreation in Zhentouba station with vibration area 15～90MW as a whole and water level 621m. Maximum energy conservationmodel has beenselected asthe economic operation strategy.

If the load change, increase or decrease, needed to be regulatedis less than 50MW, then small load model will be automatically initiated and Pubugoustation willundertaken independently the load change. Otherwise, the system will firstly adoptfast regulation model to regulate the total loadto dead zone of the target load, later it will transfer automatically to maximum energy conservationmode, reducing the load value of Pubugou at a constant speed while increasingthe load of Shenxigou 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 forregulation in each station under different strategy models are shown in Table 3.

Table 3 Comparison of load distribution and regulation among different models

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	Target load /MW	Regulation time/min
Pubugou	2180	2180	0	2380	1.34	2340	1.07	2291.1	0.75
Shenxigou	420	520	1.67	420	0	460	0.67	464.4	0.75
Zhentouba	400	500	1.67	400	0	400	0	444.5	0.75
Total	3000	3200	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 conservationmodel, namely, the target load value of Pubugou is segmentedlyreduced to 2,180MW to ensure that time needed for load reduction is almost identical to the time needed for load increaseof Shenxigou and Zhentouba; the target load value is increased to 520MW in Shenxigou, and 500MW in Zhentouba. The result of the simulated operation for 1 hour shows average water consumption rate of the three cascades is 5.22m^3/kWh under the maximum energy conservationmodel, and water consumption is 3.55% lower thanfastregulation model, the savedwater can generate additional electricity of about 110,000kWh.

It can be seen thatcascade stations can respond in the shortest time in fast regulation modelwith total load regulated in place quickly. Through twice load distribution, the three stations can operate in an economical and reasonable load zone, thus to balancethe 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 commandas hard constraints of Dadu River, the paper incorporates10 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), constructs2 kinds of safety dispatching models (fast regulation and abnormal water level) and 5 kinds of economic dispatching models (minimum water abandoning,maximum energy conservation, stable water level, less regulation and balancedload); and establishesamodel 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 outputby 120 million kWh in dry season, compared with the year 2106. However, from the perspective of practicalexperience, 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 betweenprimaryandsecondaryfrequency regulation.

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