Cascaded Hydropower "Virtual Pumped Storage Power Station" Scheduling Method and Application

Jincheng Yang[1], Changhong Deng[1,*], Zhijun Long[1], Siying Zhang[1] and Weizhou Wang[2]
[1]School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, Hubei Province, China
[2]State Grid Gansu Electric Power Company, Lanzhou 730000, Gansu Province, China
[*]Corresponding author

***Abstract*—In order to solve the problem of peak shaving capacity in power system caused by high permeability of renewable energy, this paper proposed a cascaded hydropower "Virtual pumped storage power station" scheduling method. The "Virtual pumped storage power station" model of cascade hydropower stations is established by studying the coupling relationship between each cascaded hydropower stations, simulating the operation of pumped storage power stations from both hydraulic and electrical aspects. Under the constraints of cascaded hydropower stations, the objective function of peak shaving power of "virtual pumped power station" is constructed and figured out. The simulation results prove that the cascaded hydropower scheduling from this method is able to significantly improve flexibility and economy of cascaded hydropower, and taps the peak shaving potential of cascaded hydropower sufficiently.**

Keywords—cascaded hydropower; virtual pumped storage; real-time scheduling

I. Introduction

The main development trend of modern power system is from the original fossil energy power generation to new energy power generation. By the end of 2017, China's wind power and solar power installed capacity reached 164GW and 130GW respectively, ranking first in the world. The new energy power accounts for 16.5% of the total installed capacity of the country, and in local area, new energy penetration even exceeds 50%. However, compared with conventional power generation methods such as hydropower and thermal power generation, the most fundamental difference is the randomness, discontinuity and semi-controllability of its output power. In the process of new energy development, as the penetration rate of new energy in the power grid gradually increases, the ability of the power grid to absorb new energy faces serious challenges[1-2]. It is imperative to improve the peaking capacity of the power grid and promote the consumption of new energy by the power grid. As a high-quality peak-shaving power source, pumped storage power station is more and more widely used in modern power grids because of its rapid start-up, flexibility and reliability, and green pollution-free[3-4]. But, the problem of huge investment costs and serious restrictions on regional water resources has brought difficulties to the construction of new pumped storage power stations.

Cascade hydropower joint dispatching is a kind of large-scale, strong-coupling, multi-constrained and dynamic nonlinear optimization problem[5-6]. Many scholars have carried out a lot of explorations on the establishment and optimization of cascade hydropower models, and have achieved fruitful results. The literature [7] constructs the short-term peaking model of cascade hydropower stations by aiming at the minimum maximum residual load of power grid, and the corresponding linearization processing strategy is proposed. The literature [8] takes into account the power generation efficiency of cascade hydropower stations. And the energy storage control requirements, an optimal scheduling method for the storage energy control of cascade hydropower stations is proposed. In the literature [9], from the perspective of plant network coordination, the multi-grid peaking scheduling model of cascade hydropower stations is constructed with the goal of minimum residual mean square error of the receiving power grid. However, in the research of hydropower energy optimization operation, the literature which considering the random fluctuation of wind power, making cascade hydropower participate in short-time peak shaving, and excavating cascade hydropower peaking ability under the condition of meeting the constraints of hydropower operation is less.

So, this paper deeply analyzes the coupling relationship between cascade hydropower, establishes a "virtual pumping power station" model and proposes a "virtual pumping power station" scheduling strategy to adapt to new energy consumption to improve the peak shaving capacity of the system. Finally, the modeling and analysis of eight cascade hydropower stations from Liujia Gorge to Wujin Gorge of the Yellow River in Gansu Province are carried out. The simulation results show that the proposed method can effectively excavate cascade hydropower peaking ability and provide a solution to the problem of new energy consumption.

II. Cascade Hydropower Hydraulic Coupling

Based on the cascade control mode, the hydraulic coupling relationship between cascade hydropower stations is explored.

A. Single Hydropower Station Model

1) Hydropower conversion relationship constraint: The output of a hydropower station is determined by factors such as turbine discharge, hydraulic head, and conversion efficiency[10-11]. The mathematical model of the electric energy produced by the hydropower station during the t0-t1 period is

$$P=9.81\rho\eta qh \,, \tag{1}$$

where the density of water is denoted by ρ; the conversion efficiency of water energy to electric energy is denoted by η; the turbine discharge is denoted by q; the hydraulic head is denoted by h.

2) Water level height constraint:

$$V_{j,\min} \le V_{j,t} \le V_{j,\max} \,, \tag{2}$$

where the water storage capacity of the hydropower station j in t time is denoted by $V_{j,t}$; the minimum and maximum storage capacity of the hydropower station j is denoted by $V_{j,\min}$ and $V_{j,\max}$.

3) Discharge flow constraint

$$Q_{j,\min} \le q_{j,t} + s_{j,t} \le Q_{j,\max} \,, \tag{3}$$

where the turbine discharge and spill out of the hydropower station j is denoted by $q_{j,t}$ and $s_{j,t}$; the minimum and maximum discharge flows of the hydropower station j is denoted by $Q_{j,\min}$ and $Q_{j,\max}$.

4) Hydropower station output constraint

$$P_{j,\min} \le P_{j,t} \le P_{j,\max} \,, \tag{4}$$

where the minimum and maximum output of the hydropower station j is denoted by $P_{j,\min}$ and $P_{j,\max}$.

5) Spill out constraint

$$s_{j,\min} \le s_{j,t} \le s_{j,\max} \,, \tag{5}$$

where the minimum and maximum spill out of the hydropower station j is denoted by $s_{j,\min}$ and $s_{j,\max}$.

6) Daily regulation reservoir's end water level constraint

For hydropower stations with daily adjustment capacity, at the end of the daily dispatch period, the reservoir water storage capacity should be restored to the initial position. Mathematically,

$$V_{n_d,\mathrm{end}} = V_{n_d,\exp} \,, \tag{6}$$

where $V_{k,\mathrm{end}}$ is the storage capacity of the daily regulation reservoir k at the end of the dispatching period; $V_{k,\exp}$ is the expected water storage capacity of the daily regulation reservoir k at the end of the dispatching period.

B. Hydraulic Coupling Relationship

In a cascade hydropower system with n hydropower stations, the incoming water of the first hydropower station is determined by the natural inflow, while the incoming water of the second to n hydropower stations is determined by the discharge flow and the travel time of the upstream hydropower station. The coupling relationship between different hydropower stations can be expressed by the water balance equation. Mathematically,

$$V_{j,t+1} = V_{j,t} - [q_{j,t} + s_{j,t}] + [q_{j\text{-}1,t-\tau_j} + s_{j\text{-}1,t-\tau_j}] + w_{j,t} \,, \tag{7}$$

where $w_{j,t}$ is the natural inflow of the hydropower station j; τ_j is the travel time between the hydropower station j-1 and the hydropower station j.

III. EQUIVALENT MODEL OF CASCADE HYDROPOWER "VIRTUAL PUMPING POWER STATION"

A. Pumped Storage Power Station Model

The pumped-storage power station can work in both the pumped storage state and the water discharge state, and can only work in one state at any time. The mathematical model is as follows.

$$V_{\mathrm{ch},t+1} = V_{\mathrm{ch},t} + Q_{\mathrm{rk},t} - q_{\mathrm{ch},t} - s_{\mathrm{ch},t} + W_{\mathrm{ch},t} \,, \tag{8}$$

$$W_{\mathrm{ch},t} = f(P_{\mathrm{xn},t}, h_{\mathrm{xn},t}) \,, \tag{9}$$

$$q_{\mathrm{ch},t} = f(P_{\mathrm{fd},t}, h_{\mathrm{fd},t}) \,. \tag{10}$$

Equation (9) is the water balance equation of the pumped storage power station, where the water storage capacity of the pumping station is denoted by $V_{\mathrm{ch},t}$; the inflow flow of the pumping station is denoted by $Q_{\mathrm{rk},t}$; the turbine discharge and spill out water of the pumping station is denoted by $q_{\mathrm{ch},t}$ and $s_{\mathrm{ch},t}$, whose values are 0 when the pumping station operates in the pumped storage state; the amount of water increased due to pumped storage is denoted by $W_{\mathrm{ch},t}$, whose values are 0 when the pumping station operates in the state of water discharge.

Equations (10) and (11) are hydroelectric conversion equations for pumped-storage power station, where the energy storage capacity of the pumped-storage power station is denoted by $P_{\mathrm{xn},t}$; the pumping lift is denoted by $h_{\mathrm{xn},t}$; the power generation of the pumped storage power station is denoted by $P_{\mathrm{fd},t}$; the generating head is denoted by $h_{\mathrm{fd},t}$.

B. "Virtual Pumped Storage" Hydraulic Equivalent Method

For hydropower stations with annual or seasonal adjustment capacity, the reservoir has strong regulation capacity. In short-term optimal dispatch, water can be stored to meet the needs of future water use. From the perspective of the reservoir, by making the discharge flow of the hydropower station less than the amount of incoming water, the water storage capacity of the reservoir is increased, which is equivalent to the pumped storage state of the pumping storage station; while the water discharge of the hydropower station is greater than the amount of incoming water, the storage capacity of the reservoir is reduced, which is equivalent to the water discharge state of the power station. The mathematical model of the equivalent energy storage and total energy storage is shown in equation (11) and (12),

$$P_{\text{storage},t}=\sum_{j=1}^{J}9.81\eta_j h_{j,t}[w_{j,t}+q_{j\text{-}1,t\text{-}\tau_j}+s_{j\text{-}1,t\text{-}\tau_j}-q_{j,t}-s_{j,t}], \quad (11)$$

$$E_{\text{storage},t}=\sum_{j=1}^{J}\int_{h_{j,\min}}^{h_{j,t}}9.81\eta_j\psi_j(h)h\cdot dh, \quad (12)$$

where the total energy storage capacity of the cascade hydropower is denoted by $E_{\text{storage},t}$; the minimum hydraulic head of the hydropower station j is denoted by $h_{j,\min}$; the hydraulic head - area function of the hydropower station j is denoted by $\Psi_j(h)$; the equivalent energy storage power of cascade hydropower is denoted by $P_{\text{storage},t}$. If $P_{\text{storage},t}$ is positive, it indicates that the cascade hydropower is in the pumped storage state. If $P_{\text{storage},t}$ is negative, it indicates that the cascade hydropower is in the water discharge state.

C. *"Virtual Pumped Storage" Power Equivalent Method*

There are n cascade hydropower stations in a certain basin with a certain local load, and simulate the pumping station operation together, as shown in Figure 1(a). From the point A, when the cascade hydropower generation in the basin is greater than the total load carried by it, the external performance is output power, which is equivalent to the pumped storage state of the pumped-storage power station; when the cascade hydropower generation is less than the total load, the external performance is consume power, which is equivalent to the water discharge state of the pumped-storage power station. That is shown in Figure 1(b). The mathematical model of its equivalent output power is shown in equation (13),

$$P_{\text{out},t}=\sum_{j=1}^{J}P_{j,t}-P_{\text{load},t}, \quad (13)$$

where the equivalent external power is denoted by $P_{\text{out},t}$. When $P_{\text{out},t}$ is positive, it indicates that the cascade hydropower stations are in the pumped storage state and up-regulated; when $P_{\text{out},t}$ is negative, it indicates that the cascade hydropower stations are in the water discharge state and is down-regulated.

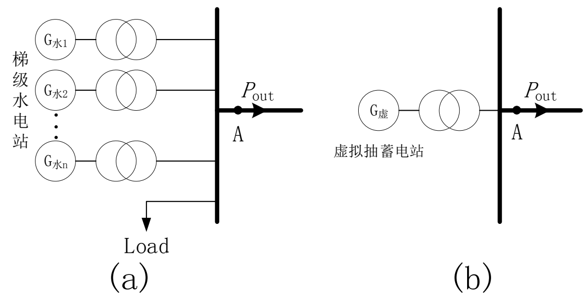

FIGURE I. EQUIVALENT DIAGRAM OF CASCADE HYDROPOWER AND ITS LOAD

IV. SCHEDULING STRATEGY OF CASCADE HYDROPOWER "VIRTUAL PUMPING POWER STATION"

The traditional cascade hydropower dispatching is to meet the load at the exit of the power station and minimize the power generation water. The strategy proposed in this paper is to meet the output power requirement of the exit of a section of the power grid (shown as point A in Figure 1) and minimize power generation water. By setting different output power plan for different time, the cascade hydropower can output the power according to the plan, fully excavate cascade hydropower peaking ability of the cascade hydropower.

A. *Minimum Output Power Deviation*

In order to make the cascade hydropower peak according to the planned power, it is expected that the deviation between the actual output power and the planned output power should be as small as possible. Mathematically,

$$\min\left[\sum_{t=0}^{T-1}a\cdot(P_{\text{out},t}-P_{\text{plan},t})^2\right], \quad (14)$$

where the scheduling period is denoted by T; the weighting factor is denoted by a; the planned output power is denoted by $P_{\text{plan},t}$.

B. *Cascade Hydropower Consumption is the Smallest*

Considering the economics of cascade hydropower, the cascade hydropower economic dispatching model is established with the goal of minimizing the water consumption of cascade hydropower. Mathematically,

$$\min\left\{\sum_{t=0}^{T\text{-}1}\sum_{j=1}^{J}(b_j\cdot q_{j,t}^2+c_j\cdot s_{j,t}^2)\right\}, \quad (15)$$

$$b_j=c_j=\begin{cases}\left(\dfrac{\eta_j}{\eta_{j+1}}\cdot\dfrac{\psi_{j+1,t}}{\psi_{j,t}}\right) & ,j<J\\ 100 & ,j=J\end{cases}, \quad (16)$$

where the reservoir area is denoted by $\Psi_{j,t}$. This objective function is designed to favor the transfer of water from large reservoirs to smaller reservoirs, allocating water in such a way as to increase system conversion efficiency.

Because this paper focuses on excavating the peaking potential of cascade hydropower, set $a>>b_j$, $a>>c_j$. In the process of solving, priority is given to the peaking target. And the objective functions used in this paper are quadratic, which not only reduces the rate of increase of bias without adding extra weight, but also constructs a convex optimization problem.

V. CASE STUDY AND RESULTS

A. Example Description

This paper takes 8 cascade hydropower stations in Liujia Gorge to Wujin Gorge of the Yellow River Basin in Gansu Province as the research object, carries out modeling and simulation in MATLAB, and calls CPLEX solver to solve the problem. Considering that these cascade hydropower stations do not participate in the peak shaving of the power grid from November to March, the historical data of April and October are used as the water supply and load of the cascade hydropower in the dry season and the wet season. In terms of economic benefits, considering the actual situation in Gansu Province, this paper takes the on-grid price of ￥0.257 per kWh and the electricity price of electricity sold at ￥0.50 per kWh. In the optimization problem, the optimization interval was 15 minutes and the time horizon was 24 hours. System parameters are given in Table I.

TABLE I. PARAMETERS FOR CASCADED HYDROPOWER STATIONS

Name	V_{max} /10^6m^3	V_{min} /10^6m^3	h /m	η /%	τ /h	Scheduling type
Liujia Gorge	4068	628	100	89.0	-	annual
Yanguo Gorge	43.01	22.86	38	89.3	2.0	daily
Bapan Gorge	28.12	19.57	18	78.4	1.0	daily
Hekou	16.38	13.64	5.3	80.0	0.5	daily
Chaijia Gorge	16.6	10.43	6.8	95.4	0.5	daily
Xiao Gorge	48	34	13.8	89.9	4.5	daily
Da Gorge	90	35	23	87.3	1.8	daily
Wujin Gorge	23.7	14.65	9.2	81.9	1.8	daily

B. Result Analysis

The simulation results are shown in Figure II-IV and Table II.

Figure II is the planned power-output power curve. It can be seen that the actual output power of the cascade hydropower varies with the planned power within a certain range, and as the absolute value of the planned power increases, the deviation between the output power and the planned power will also increase. In the dry season, the maximum peak range of cascade hydropower is [-434.44MW, 1478.45MW]; in the wet season, the maximum peak range of cascade hydropower is [-1157.2MW, 523.69MW]. In the case of not changing the total daily power generation, set the peaking plan by considering the peaking range of the cascade hydropower: in the dry season, 14 to 18 every day, the planned output power is 1500 MW, other times, the planned output power is -300MW; in the wet season, 6 to 22 every day, the planned output power is 600MW, other times, the planned output power is -1200MW.

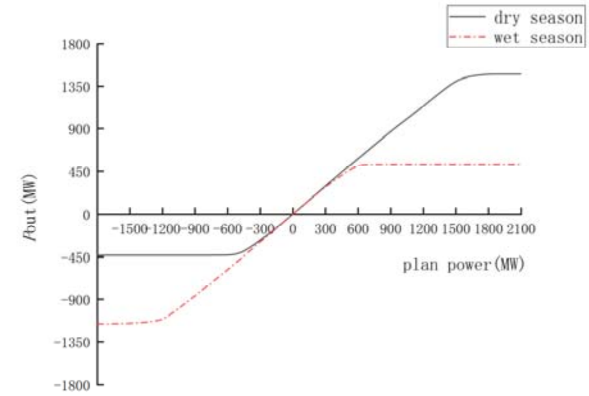

FIGURE II. PLANNED POWER-OUTPUT POWER CURVE

Figure 3 is the cascaded hydropower generation curve. It can be seen that the cascade hydropower stations operate more flexible by using "virtual pumping power station" scheduling method. Figure 3(a) shows the power generation curve of cascade hydropower in the dry season. Due to lack of water supply during the dry season, the down-regulated ability is weaker than the up-regulated ability. At 14 to 18 o'clock, considering the grid load is large, the cascade hydropower operation is in the water discharge state, and the peak is adjusted upwards to alleviate the peaking pressure of the power grid; other times, the grid load is small, so that the cascade hydropower operation is in the pumped storage state to absorb power from the grid for energy storage. Figure 3(b) is the power generation curve of cascade hydropower in the wet season. Due to the abundant water, down-regulated ability is stronger than the up-regulated ability. At 6 to 22 o'clock, the cascade hydropower stations operate in the water discharge state, and the peak is adjusted upwards; other times, the cascade hydropower stations operate in the pumped storage state and the peak is adjusted downward.

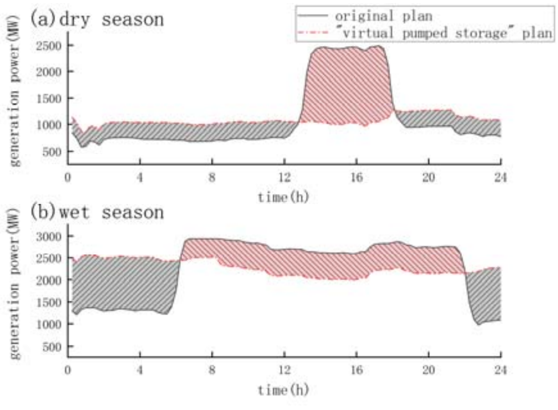

FIGURE III. CASCADED HYDROPOWER GENERATION

Figure 4 shows the output power of the section. As can be seen, the deviation between the output power and the planned power is small, which is less than 7.95% in the dry season and 13.7% in the wet season, indicating that the cascade hydropower stations can follow the generation plan.

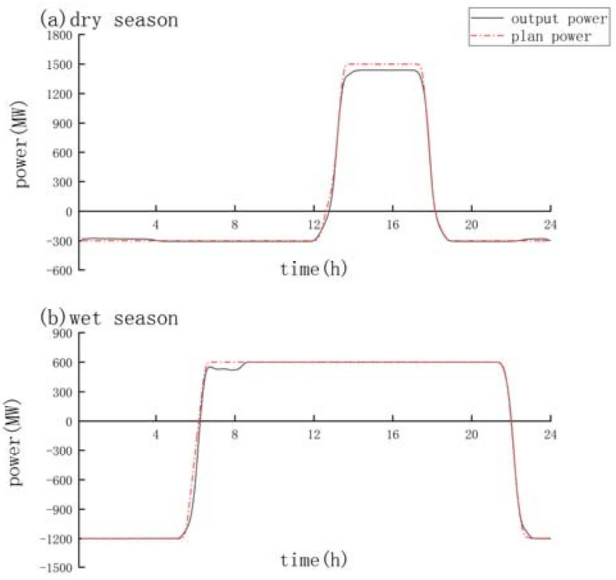

FIGURE IV. OUTPUT POWER CURVE

The original power generation plan and the virtual pumping power generation plan are compared from the aspects of peak shaving, water consumption rate and economic benefit, and the comparison results are listed in Table 2. The dry season is still in the high water period. It can be seen that no matter in dry season or wet season, the cascaded hydropower "virtual pumping power station" dispatching plan can significantly improve the peaking capacity of the cascade hydropower, and the water consumption rate changes little. In terms of economic benefits, compared with the original power generation plan, the economic benefits of the virtual pumping power generation plan are slightly reduced.

TABLE II. COMPARISON OF OPERATION RESULTS OF CASCADE HYDROPOWER STATIONS

Season	Plan	Peaking capacity /MW	Water consumption rate / m³/kWh	Benefit / million yuan
dry	original	402.5	16.057	651.9
	"virtual pumped storage"	1909.7	17.755	623.6
wet	original	575.5	16.822	1390.7
	"virtual pumped storage"	1963.2	19.145	1324.4

VI. CONCLUSION

The "virtual pumping power station" scheduling method is proposed in this paper. It equalizes cascade hydropower to pumping power station from both hydraulic and electric power, and minimizes power generation while meeting the output power requirement at the exit of a section of the power grid. The example simulation gives the peaking capacity limit of cascade hydropower in different seasons, and shows that within the limit range of cascade hydropower peak regulation, it can output power according to the plan, effectively excavating cascade hydropower peaking ability and improving the system. It also indicates that the cascaded hydropower will play an important role in future power systems containing massive amounts of renewable generation.

ACKNOWLEDGMENT

This work was supported by the National key R&D program of China (2017YFB0902200) and the Science and technology project of the State Grid Corporation of China (No.5227221600kw).

REFERENCES

[1] Zhou Q, Wang N, He S, et al. Summary and prospect of China's new energy development under the background of high abandoned new energy power[J]. Power System Protection & Control, 2017, 45(10):146-154.

[2] Ming L I, Diangang H U, Zhou Y. Research and Practice of Renewable Energy Local Consumption Mode in Gansu Province Based on “Double Alternative” Strategy[J]. Power System Technology, 2016.

[3] Tang H, Huang C, Jie D. Optimal Dispatching Schedule of Hybrid Pumped-storage Power Station[J]. Automation of Electric Power Systems, 2011, 35(21):40-45.

[4] Xu F, Chen L, Jin H, et al. Modeling and application analysis of optimal joint operation of pumped storage power station and wind power[J]. Automation of Electric Power Systems, 2013, 37(1):149-154.

[5] Hamann A, Hug G. Integrating Variable Wind Power Using a Hydropower Cascade ☆[J]. Energy Procedia, 2016, 87:108-115.

[6] Hamann A, Hug G, Rosinski S. Real-Time Optimization of the Mid-Columbia Hydropower System[J]. IEEE Transactions on Power Systems, 2017, 32(1):157-165.

[7] Chengguo S U, Wang P, Xinyu W U, et al. A Compact MILP Model for Short-Term Peak Shaving of Cascaded Hydropower Plants Considering Unit Commitment[J]. Power System Technology, 2018.

[8] Niu W, Wu X, Feng Z, et al. The Optimal Operation Method of Multi-reservoir System Under the Cascade Storage Energy Control[J]. Proceedings of the Csee, 2017, 37(11):3139-3147.

[9] P Lu, J Zhou, L Mo, et al. Method of peak operation and electric power inter-provincial coordinated distribution for cascade hydropower plants among multiple power grids[J]. Power System Technology, 2016, 40(9):2721-2728.

[10] Fang L, Zhang L. Double Layer Optimal Scheduling of Cascade Hydropower Considering Day-Ahead Peak Distribution and Flow Pulsation Stabilization[J]. Power System Technology, 2017.

[11] Hidalgo I G, Fontane D G, Arabi M, et al. Evaluation of Optimization Algorithms to Adjust Efficiency Curves for Hydroelectric Generating Units[J]. Journal of Energy Engineering, 2012, 138(4):172-178.

[12] Jia J. An Optimal Method of Short-Term Scheduling for Hydropower System With Pumped-Storage Units[J]. Power System Technology, 2017.

[13] Hirth L. The benefits of flexibility: The value of wind energy with hydropower ☆[J]. Applied Energy, 2016, 181:210-223.

[14] Xu B, Zhong P, Stanko Z, et al. A multiobjective short-term optimal operation model for a cascade system of reservoirs considering the impact on long-term energy production[J]. Water Resources Research, 2015, 51(5):3353-3369.

[15] Gebretsadik Y, Fant C, Strzepek K, et al. Optimized reservoir operation model of regional wind and hydro power integration case study: Zambezi basin and South Africa[J]. Applied Energy, 2016, 161:574-582.

[16] Shayesteh E, Amelin M, Söder L. Multi-Station Equivalents for Short-Term Hydropower Scheduling[J]. IEEE Transactions on Power Systems, 2016, 31(6):4616-4625.

[17] Wang L, Wang B, Zhang P, et al. Study on optimization of the short-term operation of cascade hydropower stations by considering output error[J]. Journal of Hydrology, 2017, 549.

[18] Hamann A, Hug G. Using cascaded hydropower like a battery to firm variable wind generation[C]// Power and Energy Society General Meeting. IEEE, 2016:1-5.

[19] Niu W, Shen J, Cheng C, et al. A Hybrid Search Method for Multi-objective Optimization Operations of Cascaded Hydropower Plants With Peak Load Regulation and Navigation Demands[J]. Proceedings of the Csee, 2016.