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Generation Scheduling Optimization of Multi-Hydroplants: A Case Study

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***Abstract*—**A case study of the generation scheduling optimization of the multi-hydroplants on the Yuan River Basin in China is reported in this paper. Concerning the uncertainty of the inflows, the long/mid-term generation scheduling (LMTGS) problem is solved by a stochastic model in which the inflows are considered as stochastic variables. For the short-term generation scheduling (STGS) problem, a constraint violation priority is defined in case not all constraints are satisfied. Provided the stage-wise separable condition and low dimensions, the hydroplant-based operational region schedules (HBORS) problem is solved by dynamic programming (DP). The coordination of LMTGS and STGS is presented as well. The feasibility and the effectiveness of the models and solution methods are verified by the numerical results.

***Keywords*—**generation scheduling, multi-hydroplants, optimization.

NOMENCLATURE

i, t, k	respectively are the index of reservoirs/hydroplants , time intervals and the prohibited operational regions of hydroplant
$E(.)$	expectation operator
n	number of the hydroplants
R_i^t	water release of ith reservoir at t
Q_i^t	natural inflows into ith reservoir at t
$\hat{Q}_i^t$	inflows forecast value of ith reservoir at t
ε_i^t	inflows forecast error of ith hydroplant at t
$¥_i^t$	electricity price of ith hydroplant at t
V_i^t	storage volume of ith reservoir at the beginning of t
T	number of the time intervals during the study horizon
$\eta_i(.)$	power generation efficiency of ith hydroplant
$F_T(.)$	the benefit-to-go function of hydroplants
$U_i^{\max}$	maximum water discharge that passes through the turbines of ith hydroplant
$V_i^{t,\min}$ $V_i^{t,\max}$	minimum and maximum storage volume of ith reservoir at t respectively
V_i^{ini} V_i^{end}	storage volume of ith reservoir at the beginning and the end of the study horizon respectively
$p_i^{t,+}$	power generation of ith hydroplant at t
$p_i^{t,-,\mathrm{in}}$	power used to pump water for ith hydroplant from the internal grid at t
$p_{i,m}^{t,-,\mathrm{in}}$	power purchased of ith hydroplant for pumping from mth hydroplant in the internal grid at t
$p_i^{t,-,\mathrm{ex}}$	power purchased of ith hydroplant for pumping from the external grid at t
α_i^t	wheeling rate of ith hydroplant at t charged by the power grid
μ_i^t	power purchasing price of ith hydroplant from the external grid
I_i^t	local inflows to ith reservoir at t
$q_i^{t,+}$ $q_i^{t,-}$	generation discharge and water pumping rate of ith hydroplant at t respectively
spl_i^t	water spillage rate of ith hydroplant at t
Ω_i	set of immediate upstream reservoirs of ith reservoir
τ_i	water traveling time from ith reservoir to its immediate downstream reservoir
$p_i^{t,\min}$ $p_i^{t,\max}$	minimum and maximum power generation of ith hydroplant at t respectively
$P_H^{t,\min}$ $P_H^{t,\max}$	minimum and maximum hydro system-wide power generation respectively
$q_i^d(k)$ $q_i^u(k)$	minimum and maximum generation discharge for kth operational region of ith hydroplant
u_i^t	operating state of ith hydroplant at t
x_i^t	number of time intervals that ith hydroplant has been on, pumping or off
x_i^{ini}	initial value of x_i^t
z_i^t	operational region that ith hydroplant is in at t
y_i^t	total startup numbers of ith hydroplant by t
ω_i^t	operating decision of ith hydroplant at t
$Ns_i^{\max}$	maximum startup number of ith hydroplant

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I. INTRODUCTION

With the deregulation of China electric power industry, the objectives and constraints of the hydropower scheduling have changed significantly. Power companies pay more attention to their own generation benefits[1]. Wuling Power Corporation (WLPC) is a subsidiary of China Power Investment Corporation and in charge of the development and operation of the hydroplants on the Yuan River Basin. The Yuan River, which originates in southeastern Guizhou, China, is the third largest tributary of the Yangtze River. According to the development planning of WLPC, there are 11 hydroplants on the main stream of the Yuan River in a top-down order of Sanbanxi (SBX), Guazhi (GZ), Tianzhu (TZ), Tuokou (TK), Hongjiang (HJ), Anjiang (AJ), Tongwan (TW), Qingshuitang (QST), Dafutan (DFT), Wuqiangxi (WQX) and Lingjintan (LJT), on the tributary You River there is Wanmipo (WMP) hydroplant, and Jinweizhou (JWZ) hydroplant on the Xiang River. Currently, the WLPC-owned hydroplants that have been put into operation include SBX, GZ, HJ, WQX, LJT, WMP, JWZ, and a pumped storage plant Heimifeng (HMF).

The WLPC-owned hydroplants have made great benefits and contributions to the local economic development since being put into operation, however, plenty of water is spilled during the flood season. As a result, to improve the water utilization efficiency and increase the benefits of the multi-hydroplants, WLPC set up a centralized control and management center (CCMC) to implement the co-scheduling of the multi-hydroplants on the Yuan River Basin. The establishment of the CCMC and the use of the hydropower information automation management system provide a platform for the improvement of the co-scheduling level of the WLPC-owned hydroplants[2].

The rest of this paper is organized as follows. Section II and III describes the LMTGS and the STGS model of WLPC-owned multi-hydroplants. Section IV gives the HBORS to avoid the hydroplants being in the prohibited operational regions. Section V presents the solution procedures to LMTGS, STGS, HBORS and the coordination of LMTGS and STGS. The numerical examples of the case study are given in Section VI, and section VII proposes the conclusions.

II. Long/Mid-Term Generation Scheduling

A. Objective Function

The LMTGS problem is to distribute the input hydro energy into shorter time intervals to maximize the expected generation benefits plus the hydro energy stored in the reservoirs, which can be formulated as follows:

$$\max_{V_i^t \; Q_i^t} E\left\{\sum_{t=0}^{T-1}\sum_{i=1}^{n}\left[\eta_i\left(V_i^t\right)\cdot \yen_i^t \cdot \min\left(R_i^t, U_i^{\max}\right)\right]+F_T\left(V_1^t,...,V_n^t\right)\right\} \quad (1)$$

where

$$Q_i^t = \hat{Q}_i^t + \varepsilon_i^t \quad (2)$$

B. Constraints

Constraints on the beginning and ending water levels of reservoir are:

$$V_i^0 = V_i^{ini} \text{ and } V_i^T = V_i^{end} \quad (3)$$

Water balance constraints on each reservoir:

$$V_i^{t+1} = V_i^t + \sum_{j\in\Omega(i)} R_j^t + Q_i^t - R_i^t \quad (4)$$

Upper and lower boundaries of reservoir storage:

$$0 \le V_i^t \le V_i^{t,\max} \quad (5)$$

And constraints on water release from each reservoir:

$$R_i^t \ge 0 \quad (6)$$

III. Short-Term Generation Scheduling

A. Objective Function

The STGS problem is to allocate the water in several days or one day into hours or minutes to maximize the generation benefits of the hydroplants, which equal to the generation benefits minus the repeated calculated internal benefits and the external power purchase cost, and can be mathematically formulated as follows:

$$\max\left\{\sum_{i,t} p_i^{t,+}\left(\yen_i^t - \alpha_i^t\right) - \sum_{i,m,t} p_{i,m}^{t,-,\mathrm{in}}\yen_m^t - \sum_i p_i^{t,-,\mathrm{ex}}\mu_i^t\right\} \quad (7)$$

B. Constraints

The constraints include the water balance constraints:

$$V_i^{t+1} = V_i^t - I_i^t + \sum_{k\in\Omega_i} R_k^{t-\tau_i} - q_i^t - \mathrm{spl}_i^t \quad (8)$$

where

$$R_i^t = \left(q_i^{t,+} - q_i^{t,-}\right) + \mathrm{spl}_i^t \quad (9)$$

Upper and lower boundaries of reservoir storage volume:

$$V_i^{t,\min} \le V_i^t \le V_i^{t,\max} \quad (10)$$

Lower and upper boundaries of water release:

$$R_i^{t,\min} \le R_i^t \le R_i^{t,\max} \quad (11)$$

Lower and upper boundaries of hydroplant-based power generation:

$$p_i^{t,\min} \le p_i^t \le p_i^{t,\max} \quad (12)$$

Hydropower system-wide power generation limits:

$$P_H^{t,\min} \le \sum_i p_i^{t,+} - \sum_i p_i^{t,-,\mathrm{in}} \le P_H^{t,\max} \quad (13)$$

Constraints on storage volume at the beginning and end of the study horizon:

$$V_i^o = V_i^{ini} \text{ and } V_i^T = V_i^{end} \quad (14)$$

IV. Hydroplant-Based Operational Region Schedules

A. Objective Function

HBORS is to avoid the hydroplant operate in the prohibited regions and is an integer programming problem. The objective function is stage-wise separable with low dimensions and is suitable to be solved by DP. When the reservoir release and hydroplant-based power generation schedules are determined, the HBORS are obtained by solving a DP process constrained by the requirements for the hydroplant-based startup and shutdown frequency and duration, and can be formulated as follows:

$$F_i^t\left(x_i^t, \mathrm{y}_i^t\right) = \max_{u_i^t}\left[g\left(u_i^t, u_i^0\right) + F_i^{t+1}\left(x_i^{t+1}, \mathrm{y}_i^{t+1}\right)\right] \quad (15)$$

where

$$g\left(u_i^t, u_i^0\right) = \begin{cases} 1 & \left(u_i^t = u_i^0\right) \\ 0 & \left(u_i^t \ne u_i^0\right) \end{cases} \quad (16)$$

and the boundary conditions are:

$$\begin{cases} F_i^T(x_i^T, \mathrm{y}_i^T) = 0 \\ x_i^0 = x_i^{ini} \text{ and } \mathrm{y}_i^0 = 0 \end{cases} \quad (17)$$

The state transition equation is:

$$\mathrm{y}_i^{t+1} = \mathrm{y}_i^t + \omega_i^t\left(u_i^t\right) \quad (18)$$

B. Constraints

Constraints on hydroplant-based operational regions:

$$\sum_k q_i^{\mathrm{d}}(k)\cdot\rho\left(z_i^t - k\right) \le q_i^t \le \sum_{k\ge 1} q_i^{\mathrm{u}}(k)\cdot\rho\left(z_i^t - k\right) \quad (19)$$

in which

$$\rho(z)=\begin{cases}1 & (z=0)\\ 0 & \text{otherwise}\end{cases} \tag{20}$$

where z_i^t=-1 means ith hydroplant is pumping water, z_i^t=1 means it is generating electricity and z_i^t=0 means it is shut down.

Hydroplant-based limits on the maximum startup number:

$$\mathrm{y}_i^t \le N\mathrm{s}_i^{\max} \tag{21}$$

where

$$\mathrm{y}_i^t=\sum_t \omega_i^t \tag{22}$$

and

$$\omega_i^t=\begin{cases}1 & \left(u_i^t \ne u_i^{t-1} \text{ and } u_i^{t-1}=0\right)\\ 0 & \text{otherwise}\end{cases} \tag{23}$$

here ω_i^t=1 means ith hydroplant is started up, otherwise ω_i^t=0.

Note that both pumping and generating belong to the hydroplant-on status, the number of the time intervals that the hydroplant keeps off is hereby amplified 100 times, and that of the hydroplant keeps pumping is represented by negative values. So the limits on the minimum number of the time intervals that the hydroplant keeps on or off are as follows:

$$x_i^{t+1}=\begin{cases}x_i^t+u_i^t & \left(x_i^t\cdot u_i^t>0\right)\\ x_i^t-u_i^t & \left(x_i^t\cdot u_i^t<0\right)\\ x_i^t+100 & \left(x_i^t\cdot u_i^t=0 \text{ and } u_i^{t-1}=0\right)\\ 100 & \left(x_i^t\cdot u_i^t=0 \text{ and } u_i^{t-1}\ne 0\right)\\ u_i^t & \left(x_i^t\cdot u_i^t\ne 0 \text{ and } u_i^{t-1}=0\right)\end{cases} \tag{24}$$

V. Solution Procedures

A. Annual-Cycle-Based Solution to LMTGS

Considering the inflows as random processes, stochastic dynamic programming (SDP) is widely used in the reservoir operation optimization[3, 4]. However, SDP will suffer from the curse of dimensionality when it comes to multi-hydroplants[5].

With the constraints and the probability distribution of inflows during each time interval tending to be the same every year when the study horizon is long enough, an assumption that the optimal trajectories of the reservoirs will duplicate themselves annually was proposed when the study horizon is long enough. Then the study horizon is divided into 3 periods, namely, the dynamic adjustment period (DAP), the annual-cycle period and the ending period. The annual-cycle-based stochastic model is made up of two sub models: an annual-cycle mode and a dynamic adjustment model. The DAP covers a transition period influenced by the real-time information. The dynamic adjustment model is to determine the reservoir storage trajectories from the observed water level at the beginning of a DAP to the annual-cycle trajectories at the end of the DAP.

Only the optimal storage derived at the end of the first time interval is used as the target to operate the reservoir, then the operation schedules are determined to guide the reservoir operation by rolling computation at the beginning of each subsequent time interval. The annual-cycle model is basically similar to the dynamic adjustment model except for the constraints on the water levels at the end of each study horizon. In the annual-cycle model, the initial water levels of reservoirs are identical with the water levels at the end of the study horizon based on the annual-cycle assumption, however, in the dynamic adjustment model, the initial water levels are the real-time observed ones and the water levels at the end of the study horizon are the ones at the corresponding time interval of the annual-cycle period. This is because the natural inflows in the dynamic adjustment model are considered as forecast-dependent random variables and are rolling updated with the change of the DAP, whereas in the annual-cycle model the inflows are tending to be the same with no difference. The stochastic model and the two sub models have been verified to be feasible and effective, more of them and the detailed solution techniques can be found in the previous work [6].

B. Hierarchical Optimization Solution to STGS

The STGS problem of multi-hydroplant is solved by decomposing the problem into the hydro reservoir system operation and HBORS. The nonlinear objective and constraints are successively approximated by first order Taylor series expansion, and p-decomposition-based algorithm is used to decompose the original problem into several sub ones by decomposing the coupling power balance. More details of the solution algorithm can be found in the previous work [7, 8].

Since STGS problem includes many complex constraints, it is difficult to define a feasible range of the constraints accurately even in the real-world operation, which might lead to non-feasible solution for the problem in the view of scheduling optimization. Therefore, a constraint violation priority is defined to deal with the situation that the artificial variables associated with the constraints are non-zero to ensure a feasible efficient solution is always derived. According to the conservation of mass, water balance constraints are not allowed to be violated; and the generation discharge through the turbines can not be greater than the reservoir release. Other involved constraints are designed to be violated as the following descending order:

1) Upper and lower boundaries of the reservoir storage volume;

2) Upper and lower boundaries of the reservoir release;

3) Upper and lower boundaries of the power generation of the hydroplant;

4) Limits on the power generation ramp of the hydroplants;

5) Constraints on the water levels of the reservoirs at the end of the study horizon.

C. Recursive DP solution to HBORS

Equation (24) is the number of the time intervals that the ith hydroplant has been on or off by (t+1). As shown in figure 1, there are 9 possible combinations in total according to the 3 different startup/shutdown statuses.

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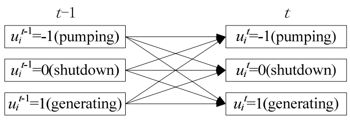


Fig. 1 Decision on startup/shutdown

Figure 2 illustrates the recursive DP procedure of the HBORS problem, and the startup/shutdown schedules of hydroplants are determined once the HBORS problem is solved.

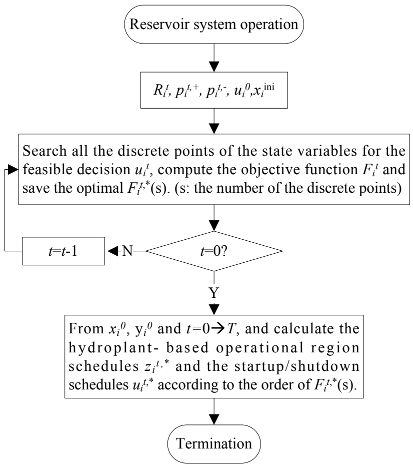


Fig. 2 Flow chart of the DP procedure

D. Coordination of LMTGS and STGS

In the real-world operation, the common ways to solve LMTGS and STGS problem are usually independent, the interactions between them are not taken into account, which probably will result in deviations from the optimal generation schedules. In other words, the benefits-to-go from the now status of hydroplants need to be considered to obtain the maximum benefits of multi-hydroplants. Therefore, it is necessary to find a way to coordinate LMTGS and STGS. LMTGS will be misleading if the forecasted inflows are considered as deterministic due to the low accuracy of the inflows forecast, and will further affect the boundary conditions of STGS. In that case, the generation schedules derived are not necessarily the optimum ones. Accordingly, a method of rolling computation and then updating the generation schedules is used to coordinate LMTGS and STGS.

As shown in figure 3, once the long/mid term generation schedules are determined (the blue line), the boundaries conditions of STGS, namely, $Z_s(0)$, $Z_s(1)$, $Z_s(2)$ and $Z_s(3)$ in figure 3, are derived by interpolations of the water level decisions of the long/mid-term schedules. With the boundaries and the observed real-time water level $z(0)$, the short-term generation schedules then can be determined (the green line). Only the water level of the first time interval, $z(1)$, is used to regulate the active operation of the hydroplant, and at the end of the first time interval, the actual water level of the reservoir may go to $z'(1)$ instead of $z(1)$ due to extra power demands or insufficient inflows, so from the second time interval, $z'(1)$ is set as the new initial condition, and the above-mentioned procedure is repeated till the end of the study horizon. Then the actual water levels of the reservoir can be derived (the red line). For instance, if the study horizon of LMTGS is 1 year, and that of STGS is T_s, then the procedure will be repeated (365-T_s+1) times.

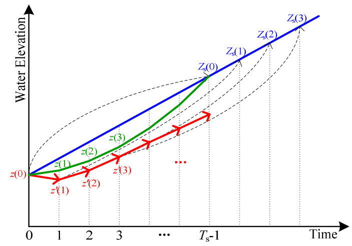


Fig. 3 Sketch diagram of the coordination of LMTGS and STGS

VI. Numerical Examples

As the top hydroplant on the Yuan River, SBX is the only hydroplant that has multi-yearly regulation ability. GZ, HJ, WMP, and WQX is capable of daily, weekly, incomplete seasonal and seasonal regulation, respectively. LJT is the last hydroplant on the Yuan River with a daily regulation reservoir. JWZ has no hydraulic connections with hydroplants on the Yuan River and is a daily regulation hydroplant. HMF is a pumped storage plant. Figure 4 is the map of the hydroplants.

Fig. 4 Map of WLPC-owned hydroplants

In the numerical experiments of this paper, the reservoir storage volumes are represented by the water levels since each reservoir has a one-to-one storage volume vs. water level curve.

A. LMTGS

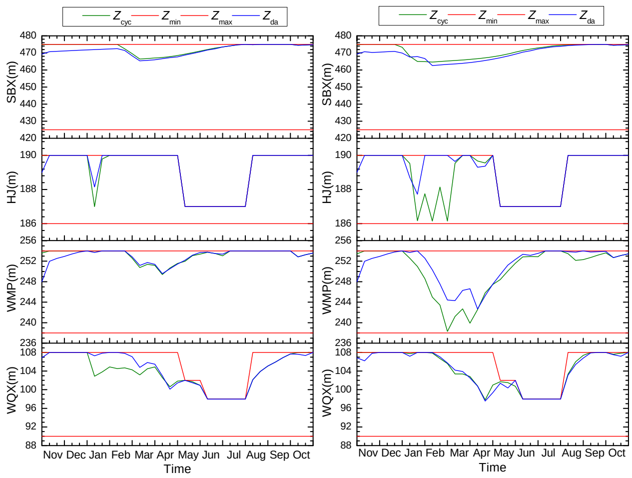
The study horizon of LMTGS is one year with 36 time intervals. In the annual-cycle model, the inflows forecast error samples are derived by runoff prediction simulation using historical runoff data of 52 years (1951-2002). In the dynamic adjustment model, the inflows of the last time interval are used as that of the current time interval. For the subsequent time intervals, the inflows are the values forecasted by AR(1). In

LMTGS, there is no need to regulate the hydroplants with low regulation ability because their small reservoirs are not able to re-distribute the water in the long term. So in this case study only the hydroplants with weekly regulation ability and above are considered. That is, only SBX, HJ, WMP and WQX are included in LMTGS problem. The data used for LMTGS are shown in table I.

TABLE I
BASIC DATA OF HYDROPLANTS FOR LMTGS

Hydro plant	Observed WaterLevel	Initial Inflows	U^{max}	h^{min}	h^{max}	V^{max}	e	α	β
	(m)	(m^3/s)	(m^3/s)	(m)	(m)	(hm^3)	(kWh/m^4)	/	/
SBX	469.3	212.8	923.0	105.5	155.5	3750.0	0.00240	3.2183	0.0755
HJ	189.0	576.7	1199.0	21.0	25.0	200.0	0.00228	0.6834	0.2217
WMP	248.0	724.3	711.0	34.5	44.5	256.0	0.00224	1.5749	0.0938
WQX	106.9	2415.9	2956.0	36.8	54.8	3048.1	0.00252	1.2415	0.6090

The optimal water level trajectories of the four reservoirs are determined by solving the long/mid-term stochastic model, and only the ending water level of the first time interval is used to regulate the reservoirs in the real-world operation. On a PC with Intel Core 2 Duo 3.0GHz and 2.0GB RAM, the total implementation time of the co-scheduling of the four hydroplants takes no more than 5s.



a. Independent scheduling   b. Co-scheduling

Fig. 5 Dynamic adjustment and annual-cycle water level trajectories

Figure 5 shows the results of the LMTGS. For the independent scheduling case, every hydroplant operates independently and have no connections with each other in terms of power compensation. As shown in figure 5.a, the annual-cycle water levels (Z_{cyc}, the same below) of the reservoirs generally decline at the low-water period to secure the electricity supply and vacate storage volumes for the upcoming flood in the flood season except HJ. This is because the reservoir of HJ has low regulation ability. Then the hydroplants basically operates with high water level and high water head. With the annual-cycle trajectories of the hydroplant as the boundary conditions of the dynamic adjustment model, the dynamic adjustment trajectories (Z_{da}) of the hydroplants then can be determined, and only the dynamic adjustment water levels at the end of the first time interval are used as the targets to operate the reservoir.

For the co-scheduling case, not only the hydraulic connections are considered, but the power compensations of the hydroplants to each other are taken into account. As figure 5.b shows, different from the independent scheduling case, the Z_{cyc} of SBX declines earlier and deeper because it needs to cover the water shortage of the downstream reservoirs in the low-water period, which simultaneously compensates for the electricity of the downstream hydroplants. This also enhances the ability of SBX to store the water during the flood season. HJ has to vacate sharply at January because of its small reservoir and the water release from the upstream SBX, which is also the main cause of the fluctuations of Z_{cyc} afterwards. The Z_{cyc} of WMP declines from the normal pool water level to the dead water level from January to February due to the water release from the upstream and the power supply demands of the low-water period. Form figure5.b, it can be seen that Z_{cyc} of WQX is clearly different from that of the independent scheduling case because WQX does not have to vacate so early, which maintains the reservoir in the high efficiency zone with high water head. Similar with the independent scheduling case, the dynamic adjustment trajectories (Z_{da}) of each hydroplant for the co-scheduling case then can be derived and the operations schedules of the multi-hydroplants are further determined according to the dynamic adjustment water levels at the end of the first time interval.

B. STGS

In STGS, the study horizon is one day with 96 time intervals, 15-minute each. The initial statuses of the reservoirs and hydroplants are the observed ones, and the boundary conditions at the end of the study horizon are derived from LMTGS. The electricity price of the peak-flat-valley-load time is shown in figure 6, other basic data of the hydroplants are as shown in table II. The STGS solving process is implemented on a PC with Intel Core 2 Duo 3.0GHz and 2.0GB RAM, and the solving time is less than 8s.

TABLE II
BASIC DATA OF HYDROPLANTS FOR STGS

Hydro plant	Capacity	z^{ini}	z^{end}	z^{min}	z^{max}	I	x^{ini}	Ns^{max}
	$(10^4 kW)$	(m)	(m)	(m)	(m)	(m^3/s)	$(15min)$	/
SBX	100.0	469.3	469.3	425.0	475.0	222.0	15	3
GZ	15.0	321.0	321.0	320.0	322.0	234.0	15	2
HJ	20.0	189.0	189.0	186.0	194.0	760.0	15	3
WMP	24.0	248.0	248.0	238.0	254.0	855.0	15	3
WQX	120.0	106.9	106.9	90.0	108.0	2577.0	15	3
LJT	27.0	49.1	49.1	49.0	51.0	2493.0	15	3
JWZ	6.0	66.0	66.0	65.0	66.0	370.0	15	3
HMF	120.0	320.0	320.0	300.0	325.0	4.0	15	3

Figure 6 is the quarter hourly power generation schedules of the multi-hydroplants, and it can be seen that the total power generation of the multi-hydroplants is basically the same with the trend of the electricity price during the study horizon. Besides, as shown in figure 6, HMF uses the energy of the low electricity price time to pump water and increase the water head and the energy stored in the reservoir. Then HMF generates electricity with high efficiency at the high electricity price time, which also verifies the effectiveness of the model.

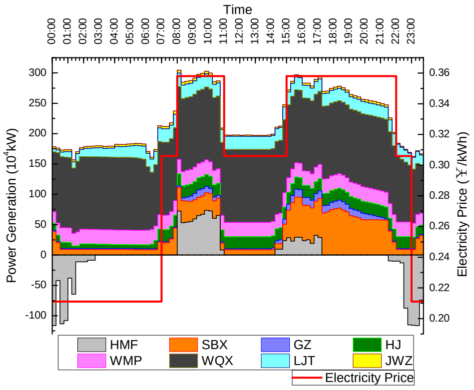


Fig. 6 Quarter hourly power generation schedules of multi-hydroplants

C. HBORS

When the power generation schedules and the water release of each hydroplant are determined, the HBORS can be determined by solving the DP problem in section IV.

Table III are the results of the HBORS of the case study, in which the symbol '+' represents that the hydroplant is generating electricity, '0' stands for the hydroplant is shut down and '-' denotes that the hydroplant is pumping water. As table III shows, neither the constraints on the hydroplant-based startup number are violated, nor are the ones on the duration of hydroplant keeping on or off.

TABLE III
HYDROPLANT-BASED OPERATIONAL REGION SCHEDULES

Time	SBX	GZ	HJ	WMP	WQX	LJT	JWZ	HMF
00:00-02:45	+	+	+	+	+	+	+	-
03:00-08:00	+	+	+	+	+	+	+	0
08:15-11:00	+	+	+	+	+	+	+	+
11:15-14:15	+	+	+	+	+	+	+	0
14:30-17:15	+	+	+	+	+	+	+	+
17:30-21:30	+	+	+	+	+	+	+	0
21:45-23:45	+	+	+	+	+	+	+	-

VII. CONCLUSIONS

In this paper, the generation scheduling optimization case study of the multi-hydroplants on the Yuan River Basin in China is reported. Based on the assumption that the optimum trajectories of the reservoirs will repeat themselves annually when the study horizon is long enough, the stochastic model of LMTGS incorporates an annual-cycle model and a dynamic adjustment model, in which the annual-cycle model is solved only once for the offline use of the dynamic adjustment model. The numerical results of LMTGS demonstrate that the model and the method are applicable to the engineering and capable of handling the real-time information of the reservoirs and hydroplants. The model of STGS incorporates pumped storage plant and comprehensive constraints. For the constraints that can not be satisfied but feasible for the real-world operation, a constraint violation priority is defined to ensure a feasible solution is always derived. Afterwards, when the power generation schedules and the water releases of reservoirs are determined, the HBORS and the hydroplant-based startup/shutdown schedules are determined by a DP procedure. The numerical results of STGS verify that the model and the methods are feasible and effective.

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