IMPROVING HYDROPOWER GENERATION SCHEDULING AND DISPATCHING DECISIONS WITH PYTHON SIMULATOR

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Variable renewable energy sources and recent developments in energy markets cause problems for hydropower plants real-time operation and unit commitment. The 15 minutes settlement period force the renewable energy asset owners to trade more frequently to balance their position, otherwise the imbalances can be very costly. In the last year, we can observe increased transaction volumes in European intraday power market (SIDC) compared to previous years. Such transactions and balancing market orders modify the generation schedules of hydropower units and increase the need for fast estimation of the lakes levels, spillage and infeasible generation units schedule. This estimation can be achieved in seconds with the generation schedules simulator proposed in this paper and implemented in Python. The simulator was tested on real data from 5 hydropower plants. The results confirm the accuracy of the algorithm and provides insights into the modelling of input data.

The article focus on presenting the details of hydropower generation schedules simulation algorithm, implementation of it in Python and testing on real data from 5 hydropower plants. The practical implementation of the algorithm allow the dispatcher to adjust the schedules of generating units and predict if they are unfeasible or spillage will occur, based on simulated levels.

Keywords: hydropower, hydropower plants, simulation, unit commitment, generation schedule, dispatch decisions, Python.

1. Introduction

Fast development of variable renewable energy resources in the last years causes serious issues for system operators to balance the power grid. Hydropower plants are the most important source of balancing services. The 15 minutes settlement period force the renewable energy asset owners to trade more frequently to balance their position, otherwise the imbalances can be very costly. In the last year, we can observe increased transaction volumes in European intraday power market (SIDC) [1] compared to previous years [2]. Large-scale battery energy storage systems were developed, but they are not significant when compared to

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storage capacity of large hydropower reservoirs. Even it is a simple task to load and unload the hydropower units, the water travel time between power plants and lakes makes [3] the generation scheduling task a complex one and time consuming for the power dispatcher.

An explicit algorithm with low computation resources for intraday market re-planning tool is [4]. The small time resolution in simulation, which is 10 seconds, compensate the disadvantage that it does not calculates exactly the water discharge and losses when a setpoint change occurs. This means that [4] is a good choice for schedules with few setpoint changes.

Special attention should be given when dealing with long simulated period reported to time resolution because small individual errors can increase at every simulation step. Nonlinearities should be taken into consideration even they increase simulation time [5, 6, 7]. With a simplified representation of the hydropower plant, as we can see in the three tests presented in [4], the simulation results will be invalidated when they are most needed, because they are far from reality.

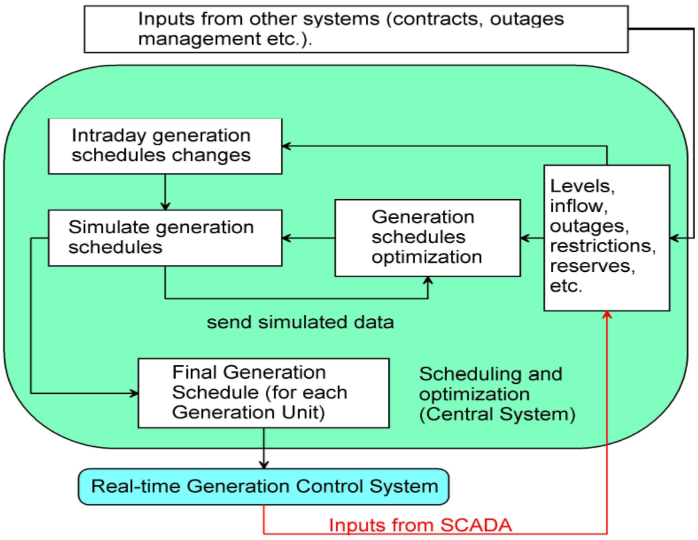


Fig. 1. Example of integration of generation schedules simulation tool in the scheduling and optimization system of one hydropower producer with multiple assets [8]

Another issue that needs to address is that an accurate simulator needs accurate representation of waterways. For free surface flow, this representation can be achieved with many measurements or with measurements combined with simulations. In [9] we used [6] for the 3D model of an open channel and [10] for the simulation of the open channel flow.

Head losses calculation details can be found in [11, 12, 13]. An improved estimation of losses in trash racks can be obtained based on [14].

The paper focus on presenting the details of hydropower generation schedules simulation algorithm, implementation of it in Python 3 and testing it on real data from 5 hydropower plants.

Development of such simulation instruments facilitates the development of generation management systems of large numbers of power generation assets. It helps the power dispatcher to take better and efficient decisions on what generation units schedules to modify and when to modify them. It also provides better visibility on hydropower assets.

2. Simulation algorithm proposal

The simulation algorithm proposed in this article was developed based on real operation of hydropower plants. The simulation algorithm has 6 important stages.

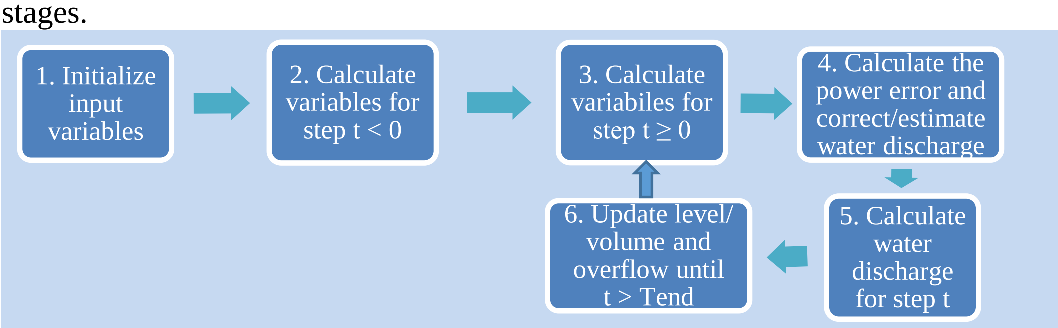


Fig. 2. Stages of simulation algorithm [9]

The initialization of the simulation with the scheduled power, levels and inflows is done in stage 1. Stage 2 calculates the water discharge of turbines and expected arrival time in downstream lakes, based on scheduled active power or measured power. Stages 3 to 6 are executed for each simulation step.

Table 1

Indices and sets

Name	Description	Name	Description
c	Index of the hydropower plant.	I_c	Set of units in plant *c*
g	Index of the hydropower plant unit.	$G_{c,g}^{in}$	Set of elements from inlet circuit of power unit g of power plant c
j	Index of the reservoir.	$G_{c,g}^{out}$	Set of elements from outlet circuit of power unit g of power plant c
i	Index of the inlet element of hydropower plant.	C_j	Set of power plants supplied from reservoir j
o	Index of the outlet element of the hydropower plant.	G_c	Set of generating units from power plant c
d	Index of the spillway structure of one dam.	t	Step of the simulation.
k	Index of the gate of the spillway.		

Table 2

Symbols

Symbol	Unit	Name
$\alpha_{j,c,i}$	s2/m5	Head loss coefficient for element i of inlet circuit of power plant c supplied from reservoir j
$a^{\%}_{j,k,d}(t)$	%	Percentage opening of valve *d* of submerged outlet *k* of reservoir *j* in time period *t*
$\theta^{simulation}$	s	Duration of one simulation step
$\eta_{c,g}(t)$	-	Overall hydropower unit efficiency of power unit g of power plant c in time period t, taken into consideration the turbine and the generator efficiency
$\eta^{estimated}_{c,g}(t)$	-	Overall efficiency of hydropower unit g of power plant c in time period t
$C_{j,k,d}(t)$	-	Flow type of spillway *k* of reservoir *j* in time period *t*
$H^{gross}_{c}(t)$	m	Gross head of hydropower plant c in time period t
$H^{net\_design}_{c,g}$	m	Design net head of hydropower unit g of power plant c
H^{max}_{j}	m	Maximum permitted level without spillage, in reservoir *j*
$H^{\max\_H}_{j}$	m	Maximum permitted level with overflow, in reservoir *j*
$H^{upstream}_{j}(t)$	m	Reservoir *j* level in time period *t*
$\Delta H^{loss}_{j,c,i}(t)$	m	Head loss for element i of inlet circuit of power plant c supplied from reservoir j, in time period t
$\Delta H^{loss\_ref}_{j,c,i}$	m	Trash rack head loss reference for element *i* of inlet waterway.
$\Delta H^{loss}_{j,c,o}(t)$	m	Head loss of element o from outlet circuit to reservoir *j* of power plant *c* in time period *t*
$\Delta P_{c,g}(t)$	MW	Active power deviation of power unit *g* of power plant *c* in time period *t*
$P^{calculated}_{c,g}(t)$	MW	Active power calculated for hydropower unit *g* of power plant *c* in time period *t*, if $t \geq 0$
$P^{nominal}_{c,g}$	MW	Rated power of hydropower unit *g* of power plant *c*
$P^{scheduled}_{c,g}(t)$	MW	Active power scheduled for hydropower unit *g* of power plant *c* in time period *t*
$Q^{overflow}_{j,k}(t)$	m^3/s	Unregulated water release through spillway *k* of reservoir *j* in time period *t*
$Q^{spill}_{j,k,d}(t)$	m^3/s	Regulated water release through gate *d* of spillway *k* of reservoir *j* in time period *t*
$N^{gate\_open}_{j}(t)$	-	Opening step of spillway gates of reservoir *j* in time period *t*, according to spillways gates opening sequence implemented
$N^{corrected}_{j}(t)$	-	Corrected opening step of spillway gates of reservoir *j* in time period *t*, according to spillways gates opening sequence implemented
$Q^{calculated}_{c,g}(t)$	m^3/s	Calculated discharge of hydropower unit *g* of power plant *c* in time period *t*, if $t \geq 0$
$Q^{corrected}_{c,g}(t)$	m3/s	Corrected discharge of power unit *g* of power plant *c* in time period *t*

$Q_{c,g}^{discharge\_estimated}(t)$	m³/s	Estimated discharge of hydropower unit *g* of power plant *c* in time period *t*
$Q_{j}^{expected}(t)$	m³/s	Expected inflow from upstream reservoirs in reservoir *j* in time period *t*
$Q_{j,c,i}^{loss\_ref}$	m3/s	Discharge taken as reference for trash rack head loss reference $\Delta H_{j,c,i}^{loss\_ref}$.
$Q_{c,g}^{nominal}$	m³/s	Rated discharge of hydropower unit *g* of power plant *c*
$\Delta Q_{j}^{spilled\_H}(t)$	m³/s	Discharge deviation in reservoir *j* in time period *t*, when maximum permitted level with overflow is exceeded
$\Delta Q_{j}^{spilled}(t)$	m³/s	Minimum water release deviation from reservoir *j* in time period *t*
$Q_{j}^{spill\_NL}(t)$	m³/s	Controlled discharge through spillways of reservoir *j* in time period *t*, reported to normal reservoir level (NL).
V_{j}^{max}	m³	Reservoir *j* volume at maximum permitted level with overflow
$X_{j,k,d}(t)$	m	Discharge depth of gate *d* of spillway *k* of reservoir *j* in time period *t*

2.1. Stage 1 of simulation algorithm

In the first stage, the input variables are initialized. The execution order of the steps in this stage is not important.

a)	Estimate natural inflow for simulated period.
b)	Initialize reservoir levels for t=0 and volumes for t=(-1).
c)	Initialize power units water discharge, natural inflow, reservoir levels and spillway gates openings for t<0.
d)	Initialize power schedule for each unit.
e)	Initialize controlled water release through spillways for t>=0.
f)	Initialize water discharge for utility for t>=0.
g)	Initialize unavailable or under maintenance spillway gates.
h)	Initialize trash rack clogging.

Fig. 3. Steps performed in stage 1

Time period t=0 is the last period when all the process variables are known.

In step 1.a) natural inflow $Q_j^{inflow}(t)$ is initialized for t≥0.

In step 1.b) only reservoir levels can be provided and the volumes can be determined from volume curves of reservoirs $V_j(t) = f(H_j(t-1))$.

In this algorithm, we consider reservoir levels from the start of time period t and volumes from the end of time period t.

Natural inflow in step 1.c) is needed for water travel time calculation.

For step 1.e), the regulated water release through spillways can be provided as flow, spillway gate opening or reservoir level restriction.

2.2. Stage 2 of simulation algorithm

In the second stage are determined or updated the variables needed in the simulation.

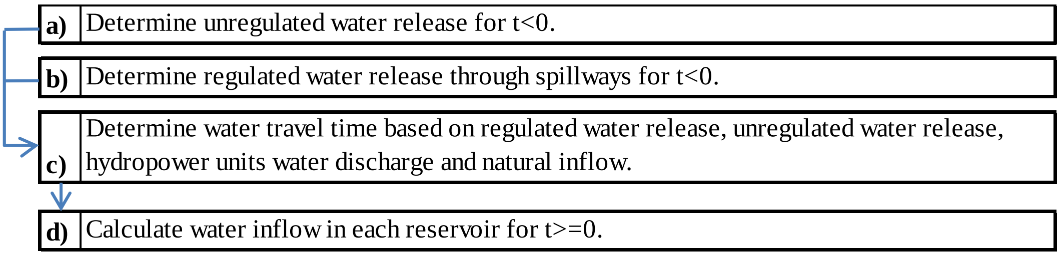


Fig. 4. Steps performed in stage 2

Unregulated water release in step 2.a) is determined based on [15]:

$$Q_{j,k}^{overflow}(t) = f\left(H_j^{upstream}(t)\right) \tag{1}$$

Equation (1) is used for crest spillways (overflow) and (2) is used for unregulated water release from pipes without gates.

For gated spillways the water release is calculated with:

$$Q_{j,k,d}^{spill}(t) = f\left(X_{j,k,d},(t);\ H_j^{upstream}(t); C_{j,k,d}(t)\right) \tag{2}$$

Flow type can be [16]:

$$C_{j,k,d}(t) = \begin{cases} 1, & for\ free\ surface\ flow \\ 0, & for\ orifice\ flow \end{cases} \tag{3}$$

For conduit spillways equipped with valves:

$$Q_{j,k,d}^{spill}(t) = f\left(a_{j,k,d}^{\%}(t);\ H_j^{upstream}(t)\right) \tag{4}$$

As we can find in [15], the tailwater effect must be taken into consideration in some cases. This can be done considering the tailwater elevation in equation 2.

Also, for different openings of adjacent gates, equation 2 can be corrected with a coefficient.

2.3. Stage 3 of simulation algorithm

In the third stage are determined or updated the variables for t≥0.

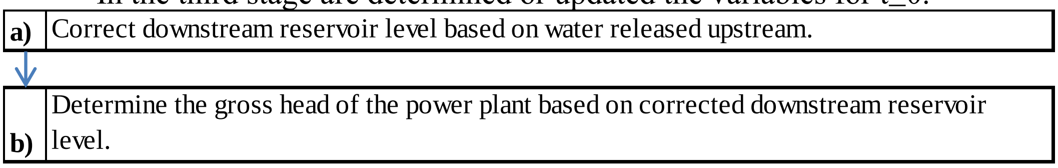


Fig. 5. Steps performed in stage 3

Step 3.a) is executed to include the backwater effect of downstream reservoir or riverbed in case of high water flow. The downstream level is considered in the reference point for gross head calculation. In our case study, the downstream level is considered at the downstream end of tailrace channel.

The gross head determined at 3.b) is be used in step 4.b).

2.4. Stage 4 of simulation algorithm

In the fourth stage is determined the generated active power and the water discharge is estimated for each power unit of the same hydropower plant.

a) Case $P_{c,g}^{scheduled}$(t-1)=0 and $P_{c,g}^{scheduled}$(t)<>0, then estimate water discharge of unit *g* with (5).

↓

b) If condition a) is not fulfilled, then calculate $Q_{c,g}^{discharge\_estimated}$(t) with (5), based on power unit efficiency at (t-1), determined with (6).

Fig. 6. Steps performed in stage 4

Discharge of one power unit is determined with [4]:

$$Q_{c,g}^{discharge\_estimated}(t) = \frac{10^6 \cdot P_{c,g}^{scheduled}(t)}{\rho \cdot g \cdot H_c^{gross}(t) \cdot \eta_{c,g}^{estimated}(t)} \tag{5}$$

Overall estimated efficiency from (5) is calculated with:

$$\eta_{c,g}^{estimated}(t) = \begin{cases} \frac{10^6 \cdot P_{c,g}^{calculated}(t-1)}{\rho \cdot g \cdot H_c^{brut}(t-1) \cdot Q_{c,g}^{calculated}(t-1)}, if\ t > 0\ and\ P_{c,g}^{scheduled}(t-1) \neq 0 \\ \frac{10^6 \cdot P_{c,g}^{nominal}}{\rho \cdot g \cdot H_{c,g}^{net\_design} \cdot Q_{c,g}^{nominal}}, if\ t = 0\ or\ P_{c,g}^{scheduled}(t-1) = 0 \end{cases} \tag{6}$$

Using this estimation of discharge, the number of iterations in stage 5 is reduced from 3 to 2 iterations.

2.5. Stage 5 of simulation algorithm

In the fifth stage, the water discharge is calculated for each power unit of the same hydropower plant.

The discharge for one power plant is determined iteratively in this stage.

In the first iteration, calculated discharge for each power unit is initialized with estimated discharge:

$$Q_{c,g}^{calculated}(t) = Q_{c,g}^{discharge\_estimated}(t) \tag{7}$$

Head losses for pressurized flow in pipes and tunnels are calculated with:

$$\Delta H_{j,c,i}^{loss}(t) = \alpha_{j,c,i} \cdot \left(\sum_{g \in I_c} Q_{c,g}^{calculated}(t)\right)^2 \tag{8}$$

For free surface flow, the head losses will be represented as matrices, based on the water level in the control point. One example of representation is in [9].

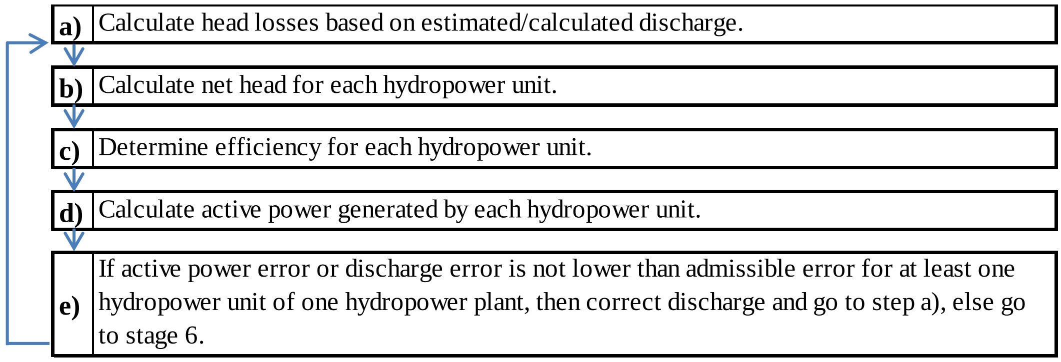


Fig. 7. Steps performed in stage 5

For trash racks, head losses will be calculated with [17]:

$$\Delta H_{j,c,i}^{loss}(t) = \Delta H_{j,c,i}^{loss\_ref} \cdot \left(\sum_{g \in I_c} Q_{c,g}^{calculated}(t) / Q_{c,g}^{loss\_ref}(t)\right)^2 \quad (9)$$

Head losses are also dependent on the clogging material (leaves, algae, branches), which can pass through racks at high discharge or can go away from the racks at very low discharge [11]. Because of this behavior, some differences will appear for different discharge values at the same clogging degree. In our case is important to determine the head loss reference at high discharge, in order to obtain minimum absolute head errors for the entire operation range of hydropower units.

Each power unit must be associated with the inlet (indices *i)* and outlet (indices *o*) elements on the waterway.

Net head will be determined based on:

$$H_{c,g}^{net}(t) = H_c^{gross}(t) - \sum_{i \in G_{c,g}^{in}} \Delta H_{j,c,i}^{loss}(t) - \sum_{o \in G_{c,g}^{out}} \Delta H_{j,c,o}^{loss}(t) \quad (10)$$

Power unit overall efficiency is determined based on net head and scheduled active power:

$$\eta_{c,g}(t) = f\left(H_{c,g}^{net}(t); P_{c,g}^{scheduled}(t)\right) \quad (11)$$

The active power of power unit will be:

$$P_{c,g}^{calculated}(t) = \frac{\rho \cdot g \cdot Q_{c,g}^{calculated}(t) \cdot H_{c,g}^{net}(t) \cdot \eta_{c,g}(t)}{10^6} \quad (12)$$

In step 5.e of stage 5 we determine active power deviation:

$$\Delta P_{c,g}(t) = P_{c,g}^{scheduled}(t) - P_{c,g}^{calculated}(t) \quad (13)$$

With equation 13 we correct the discharge:

$$Q_{c,g}^{corrected}(t) = Q_{c,g}^{calculated}(t) \cdot \left(1 + \frac{\Delta P_{c,g}(t)}{P_{c,g}^{calculated}(t)}\right) \quad (14)$$

Next, we verify:

$$|\Delta P_{c,g}(t)| < \varepsilon^{power} \quad (15)$$

$$|Q_{c,g}^{calculated}(t) - Q_{c,g}^{corrected}(t)| < \varepsilon^{discharge} \quad (16)$$

For all power units of the power plant:

$$Q_{c,g}^{calculated}(t) = Q_{c,g}^{corrected}(t) \quad (17)$$

If equations 15 or 16 are not true for at least one power unit in the hydropower plant, then we must return to step 5.a. Otherwise, we go to stage 6.

2.6. Stage 6 of simulation algorithm

In the sixth stage we determine the released water, initialize the spillway gates opening and closing and calculate each reservoir level.

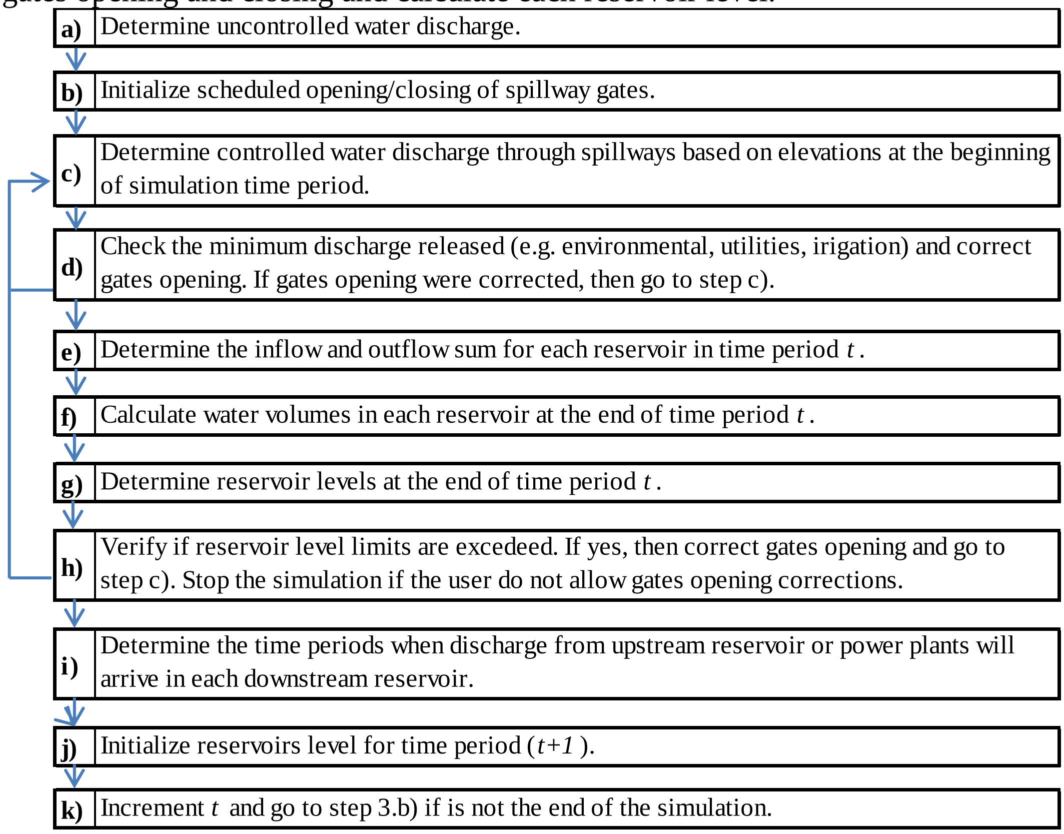


Fig. 8. Steps performed in stage 6

Operations from step 6.a are identical to the ones executed in step 2.a. Uncontrolled water discharge is determined with equation 1, depending on spillway type.

In step 6.b we initialize scheduled spillway gates opening.

Operations from step 6.c are identical to the ones executed in step 2.b. Water discharge is determined with equations 2 or 4, depending on the spillway type.

In step 6.d we verify if minimum discharge for utilities is released.

$$Q_j^{spill}(t) + Q_j^{overflow}(t) \geq Q_j^{utilities}(t) \quad (18)$$

In the primary data of the simulator is necessary to implement the spillway gates opening sequence and the discharges that correspond to rated reservoir level.

If inequality (18) is respected, then move to step 6.e. Otherwise, the spillway gates opening must be corrected.

We calculate the spilled water based on actual level in lake:

$$\Delta Q_j^{spilled}(t) = Q_j^{spill}(t) + Q_j^{overflow}(t) - Q_j^{utilities}(t) - Q_j^{normal\_overflow} \quad (19)$$

$$Q_j^{spill\_NL}(t) = f\left(N_j^{gate\_open}(t)\right) \quad (20)$$

$$Q_j^{spill\_corrected}(t) = \begin{cases} Q_j^{spill\_NL}(t) \cdot \left(1 + \frac{\Delta Q_j^{spilled}(t)}{Q_j^{spill}(t)}\right), if\ Q_j^{spill\_NL}(t) > 0 \\ \Delta Q_j^{spilled}(t),\ if\ Q_j^{spill\_NL}(t) = 0 \end{cases} \quad (21)$$

Then, we must identify the opening step of gates as if the reservoir was at rated level:

$$N_j^{corrected}(t) = f\left(Q_j^{spill\_corrected}(t)\right) \quad (22)$$

Next, correct the opening step of spillway gates:

$$N_j^{gate\_open}(t) = \begin{cases} N_j^{corrected}(t), if\ N_j^{gate\_open}(t) \le N_j^{corrected}(t) \\ N_j^{gate\_open}(t) - 1, if\ N_j^{gate\_open}(t) > N_j^{corrected}(t) \end{cases} \quad (23)$$

Run the spillway gates opening sequence and go to step 6.c.

In step 6.e, for each reservoir:

$$Q_j(t) = Q_j^{inflow}(t) + Q_j^{expected}(t) - \sum_{c\in C_j} Q_c^{calculated}(t) - Q_j^{spilled}(t) - $$
$$- Q_j^{overflow}(t) - Q_j^{irrigations}(t) \quad (24)$$

where:

$$Q_c^{calculated}(t) = \sum_{g\in G_c} Q_{c,g}^{calculated}(t) \quad (25)$$

$$Q_j^{expected}(t) = \frac{V_j^{expected}(t)}{\theta^{simulation}} \quad (26)$$

The water volume in the reservoir is calculated in 6.f:

$$V_j(t) = V_j(t-1) + Q_j(t) \cdot \theta^{simulation} \quad (27)$$

The reservoir level at the end of simulation step is determined in step 6.g as:

$$H_j^{final}(t) = f\left(V_j(t)\right) \quad (28)$$

In 6.e we must verify if the reservoir level exceeds the maximum permitted level without spillage:

$$H_j^{final}(t) > H_j^{max} \quad (29)$$

If equation 29 is not true go to step 6.i, else ask the user if:

- stop the simulation to correct the schedule;
- automatically correct the gates opening;
- continue the simulation without further actions.

The previous action are remembered for subject reservoir in the current simulation.

If the user allow for automatic gates opening, then they are corrected as in step 6.d. The discharge used for correction is:

$$\Delta Q_j^{spill\_H}(t) = \frac{V_j(t) - V_j^{max}}{\theta^{simulation}} \tag{30}$$

$$Q_j^{spill\_corrected} = \begin{cases} Q_j^{spill\_NL}(t) \cdot \left(1 + \frac{\Delta Q_j^{spill\_H}(t)}{Q_j^{spill}(t)}\right), if\ Q_j^{spill\_NL} > 0 \\ \Delta Q_j^{spill\_H}(t), if\ Q_j^{spill\_NL}(t) = 0 \end{cases} \tag{31}$$

Use equations 22 and 23 to correct the gates openings and then go to step 6.c.

In step 6.j we must initialize reservoir levels at the beginning of the next time period:

$$H_j(t+1) = f\left(V_j(t)\right) \tag{32}$$

3. Case study

To validate the proposed algorithm, we implemented it in Python 3 and we selected one sector of five hydropower plants from a real cascade hydropower system for the case study.

All hydropower units subject to study are equipped with Kaplan turbines.

The reservoirs are noted with *b1* to *b6*. The reservoirs active storage can be found in figure 9, noted with *Vu*. The maximum head variation is noted with *dH*. The power plant *c1* discharges the water in one tailrace with the length of 1194m.

Travel time (*dT*) between power plants and downstream reservoirs are represented in figure 9 and ranges between 25 minutes to 50 minutes.

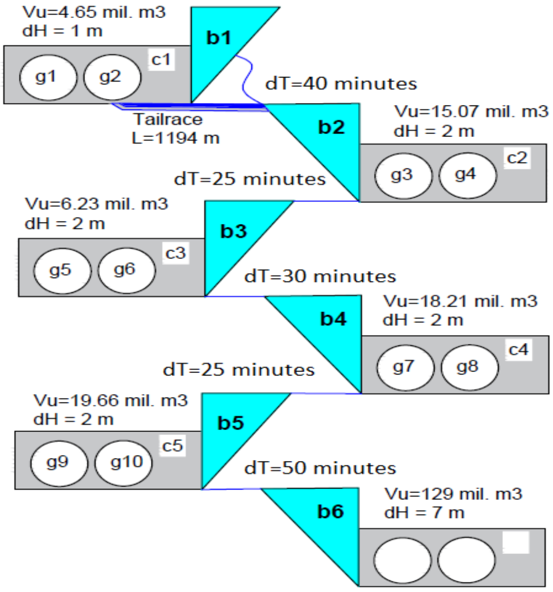
The hydraulic links between reservoirs and power plants were modeled in a matrix represented in figure 10.

Main inputs are provided as Excel files in the simulation algorithm:

- measured active power/generation schedule for each hydropower unit, at each step of the simulation;
- trash racks head loss for each hydropower unit, estimated at the beginning of the simulation;
- levels in reservoirs at the beginning of simulation;
- natural inflow in reservoirs for each step of the simulation;
- previous active power/generation schedule for each hydropower unit, for the steps that influence the simulation because of the water travel time between power plants and reservoirs.

Upstream of reservoir *b1* is another hydropower plant. The discharge from this power plant is considered as inflow in reservoir *b1*.

Downstream from reservoir *b6* is in reality another hydropower plant. The water used by that hydropower plant was considered in the simulation as negative inflow.



Power plant ID	Unit ID	Rated power [MW]	Rated discharge [m3/s]	Rated head [m]
c1	g1	22.5	165	16
	g2	22.5	165	16
c2	g3	19.75	165	13.75
	g4	19.75	165	13.75
c3	g5	20	165	13.75
	g6	20	165	13.75
c4	g7	20	165	13.65
	g8	20	165	13.65
c5	g9	23	165	15.67
	g10	23	165	15.67

Reservoir ID	Maximum level [m]	Normal level [m]	Minimum level [m]
b1	215.9	213.5	212.5
b2	199.15	198	196
b3	184.6	184	182
b4	170.43	170	168
b5	156.2	156	154
b6	141.62	140	133

Fig. 9. Simplified hydropower scheme of studied hydropower plants

Reservoir ID	Hydropower plant ID				
	c1	c2	c3	c4	c5
b1	-1	0	0	0	0
b2	1	-1	0	0	0
b3	0	1	-1	0	0
b4	0	0	1	-1	0
b5	0	0	0	1	-1
b6	0	0	0	0	1

Remark: (-1) if c2 use water from reservoir b2.

Remark: (+1) if c2 discharge water in reservoir b3.

Fig. 10. Matrix of hydraulic links between hydropower plants and reservoirs

The main outputs of the algorithm are the levels in the reservoirs.

One week was selected for the simulation, meaning that we run seven simulations, one for each 24 hours, with a simulation step of 300 seconds.

As an example, in figure 11 are represented the *c2* hydropower plant discharge, calculated based on measured active power of hydropower units *g5* and *g6*, the measured level and simulated level of reservoir *b2* for day 04.05.2024.

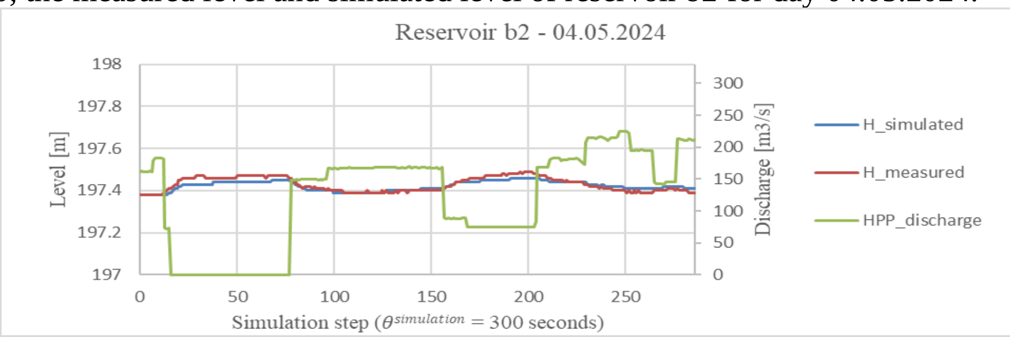


Fig. 11. Simulated and measured level for reservoir b2 in day 4 of the simulation

Measured active power were used as inputs in the simulation. The measured levels in reservoirs were compared with simulated levels. The results are presented in table 3.

Table 3

Results of the simulations

Day	Level name	Reservoir ID					
		b1	**b2**	**b3**	**b4**	**b5**	**b6**
02.05.2024	H_simulated [m]	213.19	197.63	183.52	169.64	155.71	139.37
	H_measured [m]	213.12	197.66	183.57	169.6	155.65	139.36
	H_difference [m]	0.07	-0.03	-0.05	0.04	0.06	0.01
03.05.2024	H_simulated [m]	213.03	197.49	183.45	169.5	155.72	139.41
	H_measured [m]	213.07	197.38	183.55	169.52	155.63	139.39
	H_difference [m]	-0.04	0.11	-0.1	-0.02	0.09	0.02
04.05.2024	H_simulated [m]	213.08	197.41	183.52	169.47	155.73	139.42
	H_measured [m]	213.01	197.39	183.55	169.5	155.66	139.4
	H_difference [m]	0.07	0.02	-0.03	-0.03	0.07	0.02
05.05.2024	H_simulated [m]	213.01	197.29	183.66	169.41	155.73	139.49
	H_measured [m]	212.97	197.3	183.6	169.43	155.67	139.48
	H_difference [m]	0.04	-0.01	0.06	-0.02	0.06	0.01
06.05.2024	H_simulated [m]	213.02	197.55	183.5	169.42	155.82	139.42
	H_measured [m]	213.04	197.63	183.51	169.4	155.76	139.39
	H_difference [m]	-0.02	-0.08	-0.01	0.02	0.06	0.03
07.05.2024	H_simulated [m]	213.07	197.51	183.35	169.31	155.88	139.42
	H_measured [m]	213.01	197.49	183.4	169.32	155.82	139.38
	H_difference [m]	0.06	0.02	-0.05	-0.01	0.06	0.04

6. Conclusions

Based on the differences between the measured and simulated level, we can conclude that the simulation algorithm can be used for real hydropower cascades.

The implementation of the algorithm in Python 3 provides the possibility to use it for other hydropower cascades with relatively low effort. Attention should be paid to an important and time-consuming step in the parametrization of the developed software, the step of defining the efficiency matrices for the hydropower units.

The time step (sample time) with a duration of 300 seconds is optimal because it provides good precision and speed of the algorithm. The generation schedules for one day are simulated in approximately 7 seconds.

The hardware used for the simulation has 2.6GHz CPU and 16GB RAM.

The practical implementation of the algorithm allow the dispatcher to adjust the schedules of generating units and predict if they are unfeasible or spillage will occur, based on simulated levels. Also, the simulator is part of an iterative optimization-simulation algorithm that will provide data (generation units schedules) to an Automatic Generation Control System of one large hydropower producer.

The case study did not simulated scenarios with water spillage, mainly because the lack of data. The algorithm will be further developed and tested [18].

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