

Hydraulic Design Challenges of High Head 880 MW Gouvães Pumped-Storage Power Plant

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Abstract. The 880 MW pumped-storage power plant of Gouvães, which is part of the Alto Tâmega hydro power scheme from Iberdrola is currently under construction in the north of Portugal. The power plant is equipped with 4 reversible Francis pump-turbines with a gross head of 660 m. The power plant features several challenges with respect to the hydraulic design such as: i) ultra-high-head single stage reversible Francis pump-turbine of very low specific speed leading to severe hydraulic transients, ii) a long high-pressure penstock, iii) an headrace differential surge tank linked to a 4700 meters long headrace tunnel and iv) a complex tailrace differential surge tank linked to a 700 meters long tailrace tunnel. To perform the hydraulic design of the pumped-storage power plant, a stepwise approach presented in the paper was undertaken by Iberdrola. A detailed 1D hydraulic transient analysis was performed to optimize the headrace and tailrace surge tank dimensions. Then a combined CFD and reduced scale physical transient tests of both surge tanks was conducted. This enabled to address the complex 3D flow physics that develop in surge tanks but are not captured by 1D transient simulations such as free surface, upsurges against walls, verification of throttle singular head losses and effects not captured by 3D CFD such as air-water mixture and detection of air entrainment risk.

1. Introduction

The 880 MW pumped-storage power plant, PSPP, of Gouvães, which is part of the Alto Tâmega hydro power scheme from Iberdrola is currently under construction in the north of Portugal, [1]. The energy storage and grid regulating plant is equipped with 4 reversible Francis pump-turbines with nominal power of 220 MW, a gross head of 660 m and a total discharge of 160 m³/s in turbine mode and 128 m³/s in pumping mode. The power plant features several challenges with respect to the hydraulic design such as: i) ultra-high head single stage reversible Francis pump-turbine of very low specific speed $N_{qp}=26$ leading to very pronounced S-shape 4 quadrants characteristics which may lead to severe hydraulic transients, ii) a high pressure penstock of about 2160 meters long, iii) an headrace differential surge tank linked to a 4700 meters long headrace tunnel and iv) a complex tailrace differential surge tank linked to a 700 meters long tailrace tunnel. Consequently, to accommodate the hydraulic design, challenges of the pumped-storage power plant, a stepwise approach presented in the paper was undertaken by Iberdrola.

First, a 1D simplified hydraulic transient simulation was performed by the project engineering team to define general hydraulic layout. Then a detailed 1D hydraulic transient study including realistic Francis pump-turbine 4 quadrants characteristics to optimize the headrace and tailrace surge tank dimensions was carried out. Finally, a combined 3D unsteady CFD and reduced scale physical transient tests with a scale ratio of 1:25 of both tailrace and headrace surge tanks were conducted. This last step of surge tank optimization enabled to address and visualize the complex flow physics that are not captured by 1D transient simulations such as free surface flow developing in the surge tanks with gravity waves and surge waves, upsurges against walls, verification of local hydraulic throttle loss and effects not sufficiently captured by 3D CFD, such as water-air mixture related aspects to prevent air entrainment associated risks for the waterway and the air release of the surge tank structure. Moreover, the load cases

considered in the multi-disciplinary approach include unfavorable multiple loading and unloading of the 4 units in phases with both headrace and tailrace surge tanks for the mass oscillations in order to capture the most extreme hydraulic transient. This approach allows for this specific flexible pumped-storage power plant a robust operation range for improved integration of large shares of new renewable energies in the Portuguese electrical power network.

2. Gouvães PSPP description

The hydraulic layout of the 880 MW Gouvães pumped-storage power plant, PSPP, is presented in Figure 1. The power plant includes:

- the upstream reservoir of Gouvães with water levels varying between 873 masl to 885 masl;
- an upstream gate shaft;
- a headrace tunnel of about 4'700 m with diameter of 7.3 m;
- a differential Johnson surge tank with a gate shaft with diameter of 8 m which can spill into a 21 m diameter main riser connected to the headrace tunnel with a throttle, see Figure 2;
- a penstock of about 2'200 m with diameter of 6 m on the upper part then reduced to 5.4 m, and then to 3.8 m on the lower part where it splits in two pipes twice to feed the four units, see Figure 1 and Figure 3;
- a power house with 4 units equipped with ultra-high-head single stage reversible Francis pump-turbines and synchronous generator which characteristics are provided in Table 1;
- a tailrace surge tank with upper and lower surge chambers; the lower chamber being connected to each unit draft tube tunnel by a specific connecting shaft of 3.5 m of diameter, see Figure 3;
- a common tailrace tunnel of 700 m and 7.3 m of diameter;
- a downstream gate shaft;
- the downstream reservoir of Daivões with water levels between 219 masl and 228 masl.

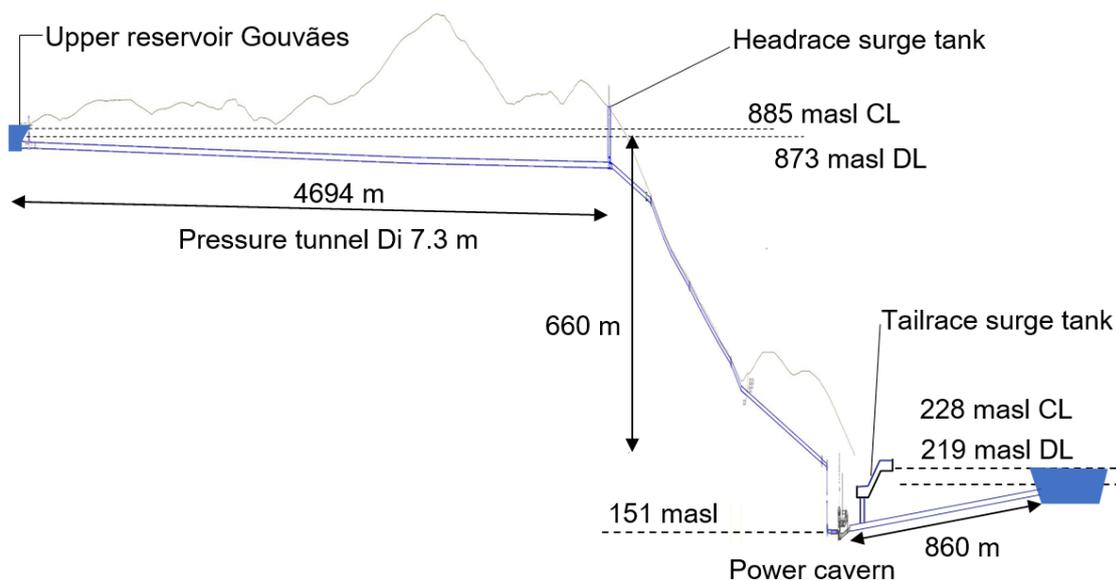


Figure 1. Waterway layout of the Gouvães 880 MW PSPP.

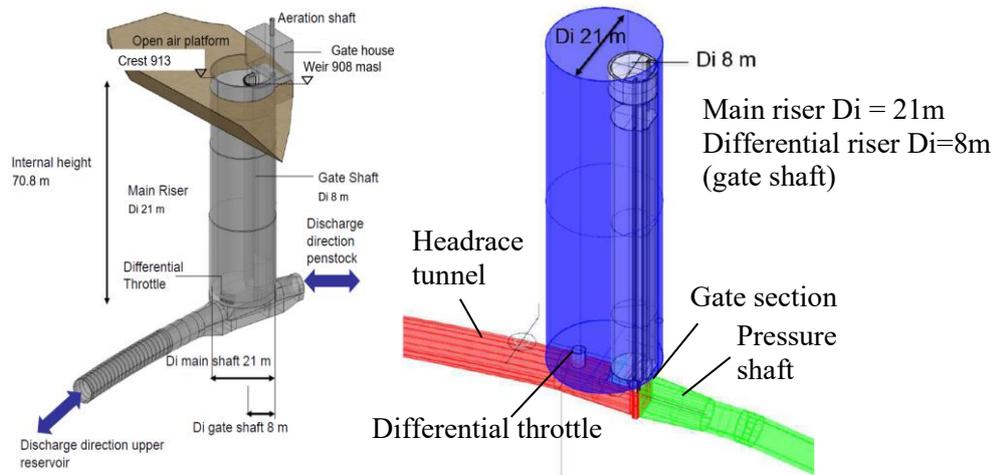


Figure 2. Layout of headrace differential surge tank of the Gouvães PSPP.

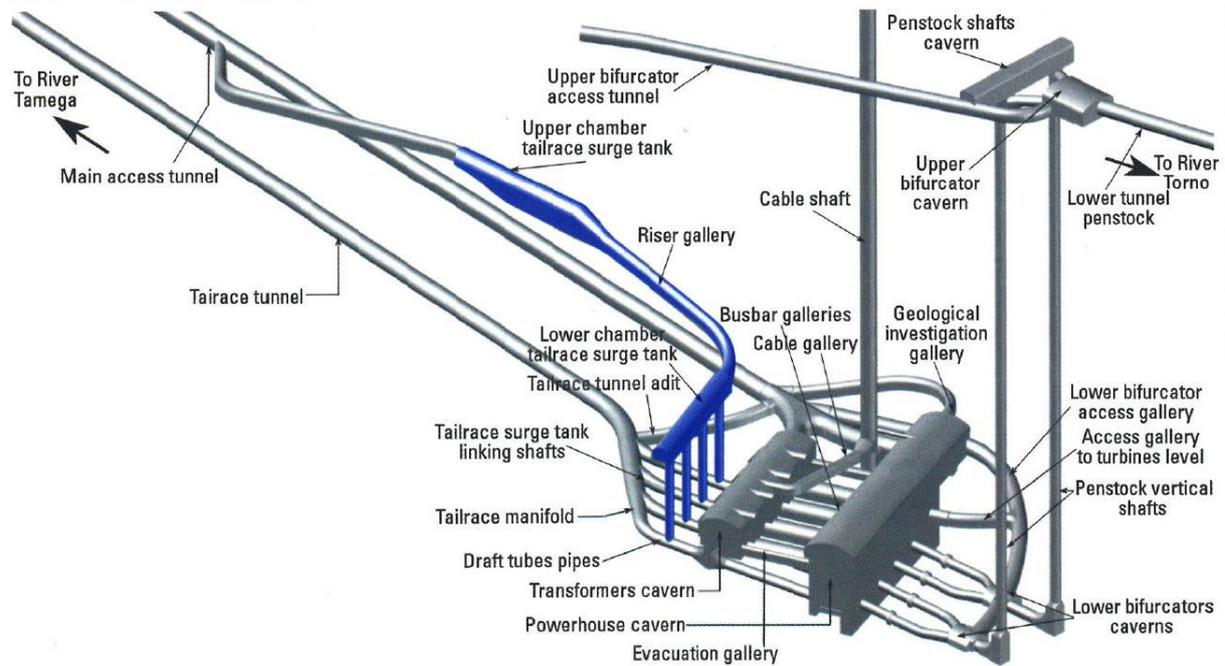


Figure 3. Layout of the underground powerhouse of the Gouvães PSPP and tailrace surge tank (in blue) and related access tunnels.

Table 1. Gouvães pump-turbines characteristics.

Description	Values
Nominal power P_n	232 MW
Nominal head H_n	660 mWC
Nominal discharge turbine mode Q_{nt}	40 m ³ /s
Nominal discharge pump mode Q_{np}	-32 m ³ /s
Nominal rotational speed N_n	600 rpm
Runner reference diameter D_{ref} (Low pressure side)	1.55 m
Mechanical time constant T_m	7.2 s
Pump specific speed N_{qp}	26

3. Iterative surge tank design methodology

Since Gouvães PSPP includes long headrace and tailrace tunnels, it was necessary to include headrace and tailrace surge tanks to accommodate water hammer phenomena, [2], [3]. During the preliminary design phase Iberdrola performed 1D numerical simulations with simplified models of pump-turbines to develop the first design of the headrace and tailrace surge tank of the PSPP considering hydraulic transient, civil structure design, project planning and geological aspects. It was found advantageous to have a tailrace surge tank which include upper and lower expansion chambers linked with an inclined gallery, see [4]. A particular attention was already paid to reduce as much as possible the distance between the pump-turbine unit and the tailrace surge tank in order to mitigate as much as possible risk of water column separation which may arise in low specific speed reversible Francis pump-turbines featuring a pronounced “S-shape” characteristic, see [5]. This was made possible thanks to the 4 vertical connecting shafts linking the lower expansion chamber to the 4 draft tube tunnels, with a minimum distance to the units in order to minimize the corresponding hydraulic inertia, see [6].

In a second stage, Power Vision Engineering performed the first optimization of the headrace and tailrace surge tanks using 1D SIMSEN software [7] modelling of Gouvães PSPP including a realistic 4 quadrants characteristics of the low specific speed reversible Francis pump-turbine. During this phase, the upper and lower expansion chambers were moved respectively further up and down in elevation while the chamber cross sections were narrowed with an increased height to make them more effective to accommodate the tailrace mass oscillations. The diameter of the 4 vertical connecting shafts which influences both hydraulic inertia and singular head losses of the tailrace surge tank inlet connection, were optimized in order to improve minimum draft tube pressure in case of pump-turbine delayed load rejection, [8] and covering a blocked guide vane load case with MIV closing. Finally, the singular head losses of the headrace surge tank were optimized to achieve optimal headrace mass oscillations behavior while preventing from the risk of top penstock and headrace tunnel low pressure in case of pump power failure, [9].

In a third stage, TU Graz Institute of Hydraulic Engineering and Water Resources Management performed a second step surge tank optimization with hybrid modelling approach, combining 1D transient calculation, 3D CFD and reduced scale physical model tests, [10], [11], [12], as further described in chapter 5. The headrace surge tank was modified at this stage in order to mitigate uplift forces on the penstock protection gate in case of turbine emergency shutdown, ESD, by using a so-called Johnson differential design for the headrace surge tank, where the gate is located in the small 8 m diameter differential shaft which is not anymore subject to excessive pressure differences responsible for the large uplift force, see [12]. The results of the physical transient model test of headrace and tailrace surge tanks were used together with the pump-turbine 4 quadrants characteristics measured during official model tests performed at ANDRITZ Hydro in Graz, as inputs for the final 1D transient analysis. The guide vane and main-inlet valve, MIV, opening and closing laws were optimized by the pump-turbine supplier as part of their 1D transient analysis and were also considered for the final 1D transient analysis verification described in chapter 4. Control stability of the units and possible interactions with the surge tanks were verified with Svec stability criteria, [13], and by 1D numerical simulations including realistic PID turbine governor.

4. 1D Transient analysis

4.1. SIMSEN model of Gouvães PSPP

Figure 4 presents the SIMSEN simulation model of Gouvães PSPP corresponding to the final hydraulic layout which includes the upper reservoir and gate shaft, the headrace tunnel, the detailed model of the headrace differential surge tank, the penstock, the 4 reversible Francis pump-turbine modelled with their 4 quadrants characteristics and the total angular inertia of the pump-turbine and synchronous generator, the draft tubes tunnels, the detailed model of the downstream differential surge tank and the 4 connecting pipes to the draft tube tunnels, the downstream manifold, the tailrace tunnel and lower gate shaft and the lower reservoir.

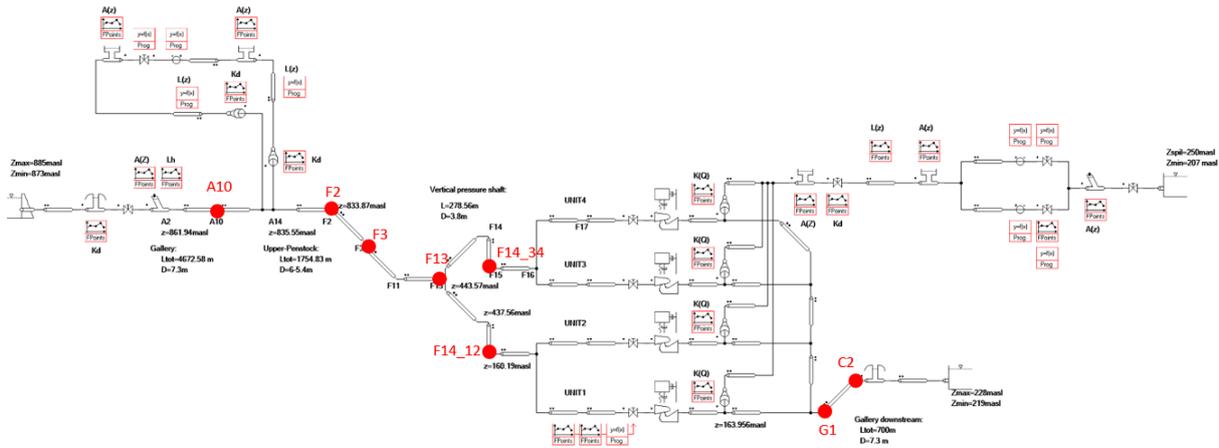


Figure 4. SIMSEN simulation model of the Gouvães PSPP.

The specific inflow/outflow singular head loss coefficients of both surge tanks were determined first by 3D CFD computation and then updated based on reduced scale physical model tests of both surge tanks performed at TU Graz Institute of Hydraulic Engineering and Water Resources Management, see chapter 5.

4.2. Transient simulation results of Gouvães PSPP

The Table 2 provides the definitions of the water level conditions considered for the 1D transient analysis of Gouvães PSPP which include the following type of load cases:

- **Normal load cases:**
 - Start-up, loading, unloading and normal shutdown;
 - Emergency shutdown (ESD), Quick shutdown (QSD);
 - Delayed load rejection;
 - Any combination of normal load cases;
- **Exceptional load cases involving failure of components:**
 - ESD with 1 guide vane failing to close;
 - ESD with 1 main inlet valve (MIV) failing to close;
 - ESD with GVO closing on the security diaphragm.

Table 2. Gouvães PSPP reservoirs water level conditions definitions.

Definition	Upper reservoir	Lower reservoir	Gross head
Hmax	Max = 885 masl	Min = 219 masl	666 mWC
Hmin	Min = 873 masl	Max = 228 masl	645 mWC
Zmax	Max = 885 masl	Max = 228 masl	657 mWC
Zmin	Min = 873 masl	Min = 219 masl	654 mWC

Several normal and exceptional load cases in both operating modes were simulated to assess the overall transient behavior of the Gouvães PSPP. Table 3 provides the description of the load cases that were found to be the most critical for the headrace and tailrace surge tank during the final verification. The normal and exceptional load cases are subject to different safety margins due to the difference of probability of occurrence. It is interesting to mention that an increased loading time of 90 seconds for a power ramp from speed no load to full nominal power was part of the solution necessary to accommodate the extreme mass oscillations transient load cases. To achieve a robust design while ensuring a high flexibility of the power plant, see [10], the exceptional load cases include resonance load cases in turbine mode with several loading and unloading events in unfavorable time coupling with the surge tanks mass oscillations to prevent from surge tank dewatering or spilling consequences, see [14]. The simulation

results of the normal critical load cases of the headrace and tailrace surge tanks are presented respectively in Figure 5 and Figure 6. The results of the exceptional load cases are presented in Figure 7 and Figure 8. The simulation results show the transient evolution of the key pump-turbine quantities, such as the head h , the discharge q , the mechanical torque t , the rotational speed n , the guide vane position y , the MIV position y_{MIV} , all represented in per unit (pu) values. The simulation results of the surge tanks include the transient evolution of the water levels HCSTUP1,2 and discharges QSTUP1,2 of the headrace surge tank gate shaft ($D = 8$ m) and main riser ($D = 21$ m), and the water levels HCSTDW1,2,3 and discharges QSTDW,2,3U of the tailrace surge tank lower chamber, riser and upper chamber and QSTDW3D is the discharge through the bottom of the weir, where water levels relate to left vertical axis while discharges relate to right vertical axis.

One can notice that the critical load cases combine various types of load cases, for this particular power plant, the maximum headrace surge tank and minimum tailrace surge tank water levels are driven by turbine load cases, while the minimum headrace surge tank and the maximum tailrace surge tank load cases are driven by pump load cases.

Table 3. Description of critical load cases for Gouvães PSPP surge tanks (where TU: turbine mode; PU: pump mode).

	Load case	Water levels	Description	Surge tank critical quantity
Normal	TU2A	Zmax	Simultaneous loading of 4 Units from 0 % to 100 % of nominal power P_n followed by an ESD at most unfavourable moment	Headrace surge tank maximum level
	PU5B	Hmin	2 pumps are in operation and loading of the two other pumps followed by an ESD at most unfavourable t moment	Headrace surge tank minimum level
	PU5C	Hmin	2 pumps are in operation and loading of the two other pumps followed by an ESD at most unfavourable moment	Tailrace surge tank maximum level
	TU4	Zmin	Simultaneous loading from 0 % to 100 % of nominal power P_n of 4 Units followed by an ESD at most unfavourable moment	Tailrace surge tank minimum level
Exceptional	TU11	Zmax	Simultaneous loading of 4 units from 0 % to 100 % of nominal power P_n followed by simultaneous unloading from 100 % to 0 % of P_n followed by simultaneous reloading of 4 units from 0 % to 100% of nominal power P_n followed by ESD at most unfavourable moment	Headrace surge tank maximum level
	PU4B	Hmin	Simultaneous loading of the 4 pumps followed by ESD at most unfavourable moment (normally not possible to start 4 pumps simultaneously due to auxiliaries' systems)	Headrace surge tank minimum level
	PU4C	Hmin	Simultaneous loading of the 4 pumps followed by an ESD at most unfavourable moment (normally not possible to start 4 pumps simultaneously due to auxiliaries' systems)	Tailrace surge tank maximum level
	TU10	Zmin	Simultaneous loading of 4 units from 0 % to 100 % of nominal power P_n followed by simultaneous unloading from 100 % to 50 % of nominal power P_n followed by 4 units full guide vane fast opening resulting from large frequency deviation (primary control) followed by ESD at most unfavourable moment	Tailrace surge tank minimum level

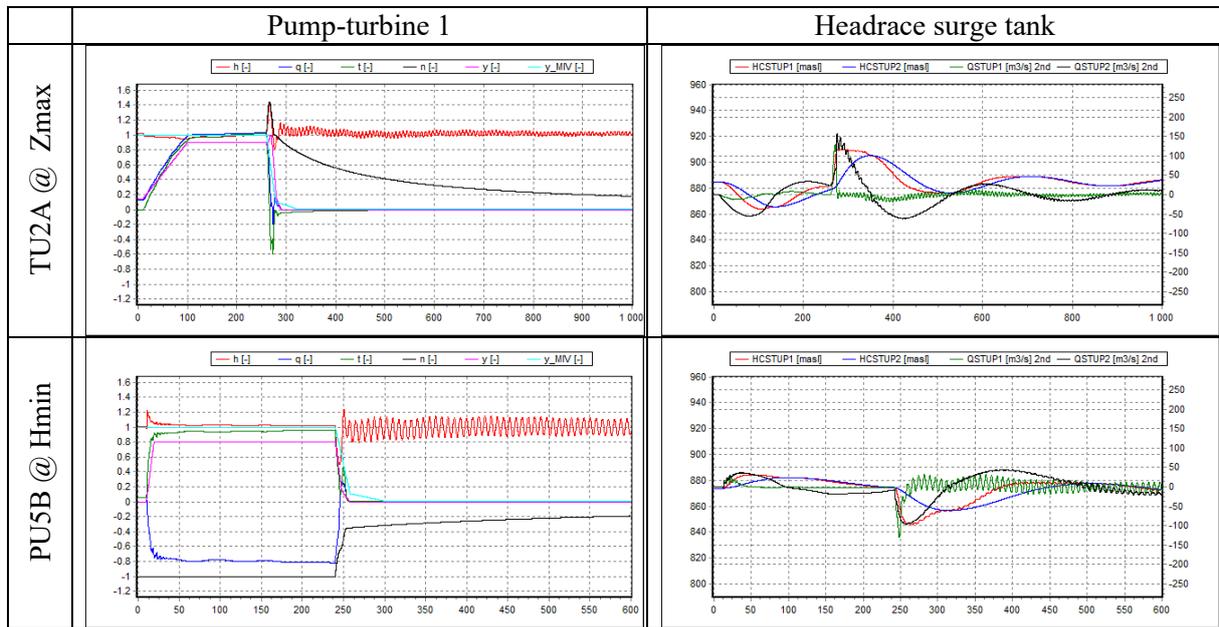


Figure 5. Numerical simulation results of the transient behaviour of the pump-turbine 1 and headrace surge tank related to critical **normal** load cases for the headrace surge tank maximum (top) and minimum (bottom) transient water levels.

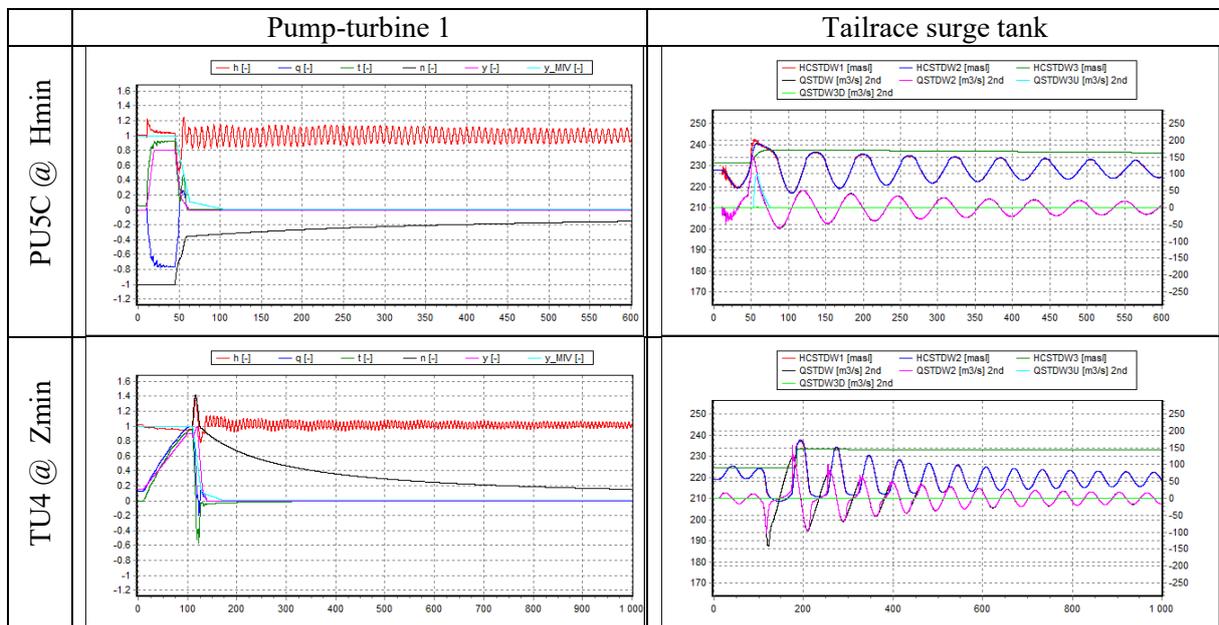


Figure 6. Numerical simulation results of the transient behaviour of the pump-turbine 1 and tailrace surge tank related to critical **normal** load cases for the tailrace surge tank maximum (top) and minimum (bottom) transient water levels.

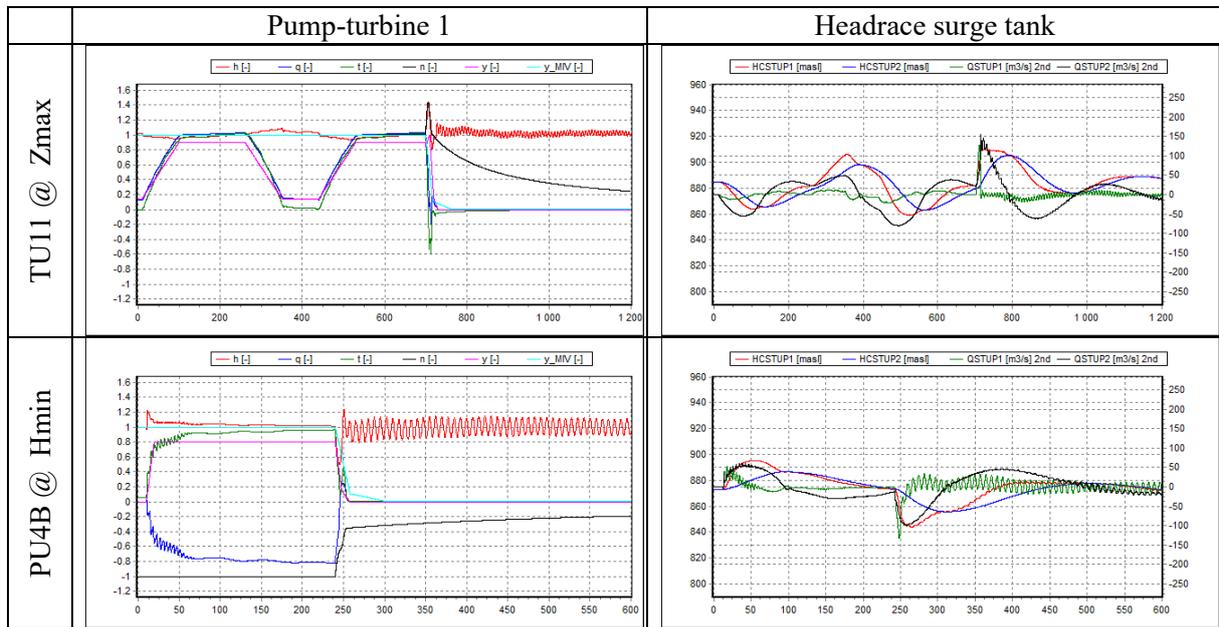


Figure 7. Numerical simulation results of the transient behaviour of the pump-turbine 1 and headrace surge tank related to critical **exceptional** load cases for the headrace surge tank maximum (top) and minimum (bottom) transient water levels.

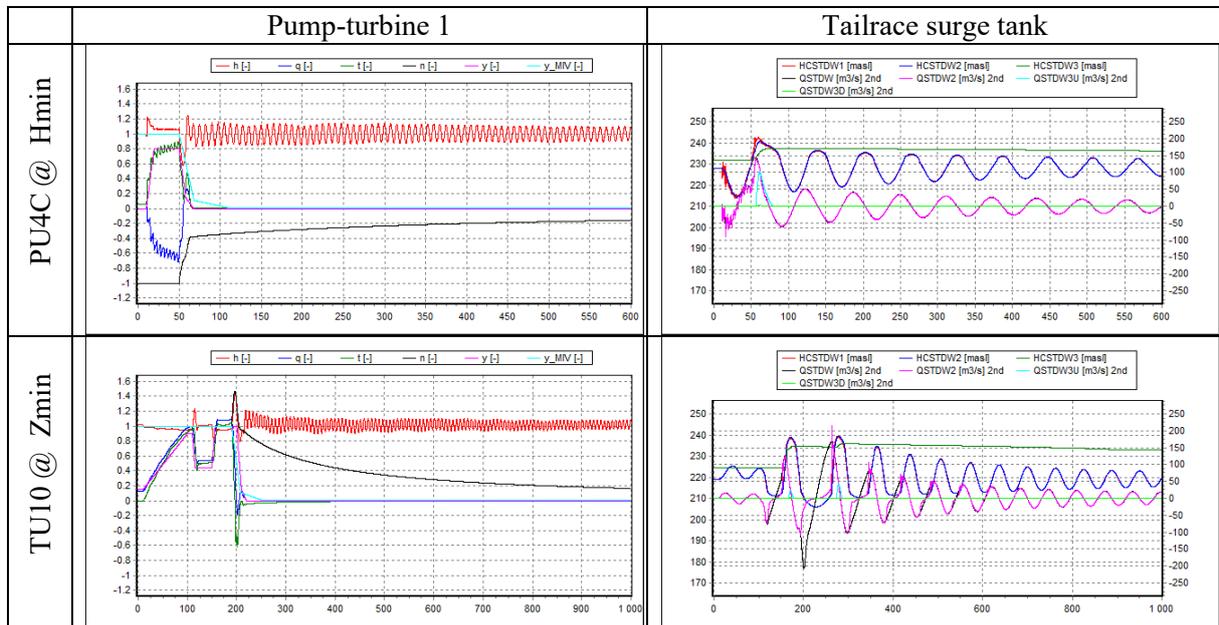


Figure 8. Numerical simulation results of the transient behaviour of the pump-turbine 1 and tailrace surge tank related to critical **exceptional** load cases for the tailrace surge tank maximum (top) and minimum (bottom) transient water levels.

5. Surge tank physical model transient tests

5.1. Motivation of surge tank physical model transient tests

The surge tanks of pumped-storage power plants are key hydraulic components to ensure proper transient behavior of the whole power plant to achieve a safe and reliable operation especially under flexible operation. The 1D transient analysis allows to optimize the volume and singular head losses of the surge tanks, but does not reflect the complex 3D flow conditions and unsteady free surface as well as two-phase flows that develops within the surge tanks during transient events. Therefore, to achieve a safe hydraulic design Iberdrola decided to perform physical model transient tests of both headrace and tailrace surge tanks at Graz University of Technology hydraulic laboratory.

Both tests were performed with a scale ratio 1:25 and considering Froude similitudes to scale down the transient discharges to feed both surge tanks to replicate dominant transient critical load cases at reduced scale. Therefore, the following similitude between model and prototype denoted with superscripts M and P respectively, apply on physical model tests:

$$Fr = \sqrt{\frac{E}{g \cdot D}} \rightarrow \frac{H^M}{H^P} = \frac{D^M}{D^P} = \frac{1}{25} \quad (1)$$

The transient discharges which flow in and out from the surge tank are obtained by 1D transient simulation that considered realistic pump-turbine transient discharge time evolution resulting from the pump-turbine S-Shape characteristic and provided by the pump-turbine supplier as boundary condition. Then, the transient 1D discharge time history is used as setpoint to control 2 valves driven by PID governor to achieve the desired surge tank discharge inflow/outflow boundary condition which is measured with IDM flow meter. The transient discharge boundary conditions have shown a very good agreement with the discharge setpoint, [4], ensuring to feed the surge tanks with a realistic physically driven transient discharge.

The physical transient tests of the surge tanks allow to assess complex transient phenomena such as the gravity free surface waves propagations, wall shocks, two phases flow and risk of air entrainment in the pressurized water system, possible air entrapment at chamber ceiling, which are not included in 1D transient analysis and remain still challenging to address accurately with 3D unsteady CFD as well as water-air mixtures. Some CFD simulation were performed by TU Graz, particularly to design and optimize the headrace surge tank differential throttle to produce the target asymmetrical singular head losses with higher head losses for inflow than for outflow. Key findings and design optimizations of headrace and tailrace surge tanks are summarized in the next subchapters, while detailed information can be found in [11], [12], [4].

5.2. Headrace surge tank transient tests key results and optimizations

Figure 9 shows examples of transient flow developing in the Gouvães headrace surge tank reduced scale model for the critical exceptional load case TU11, see description in Table 3. Most unfavorable load cases were investigated during the transient tests to:

- confirm extreme transient free surface water levels for up-surge and down-surge for the most extreme exceptional load cases and confirm there is no risk of air entrainment in headrace tunnel;
- optimize the design of the weir to achieve proper spill flow, see Figure 9 right;
- determine the minimal operational upper reservoir water level under which it would be possible to start and shutdown 4 pumps simultaneously, load case PU4B, to achieve sufficient margin to prevent from risk of air entrainment in the headrace tunnel. Advantage in this case of a physical test is to simulate hydraulic failure judging the consequences; this load case will not be possible during the first years of operation of the Gouvães PSPP due to auxiliaries' limitations, but which might be of interest for increased operational flexibility in the future;
- measure and validate the singular head losses at the inlet of the gate shaft and of the differential throttle.

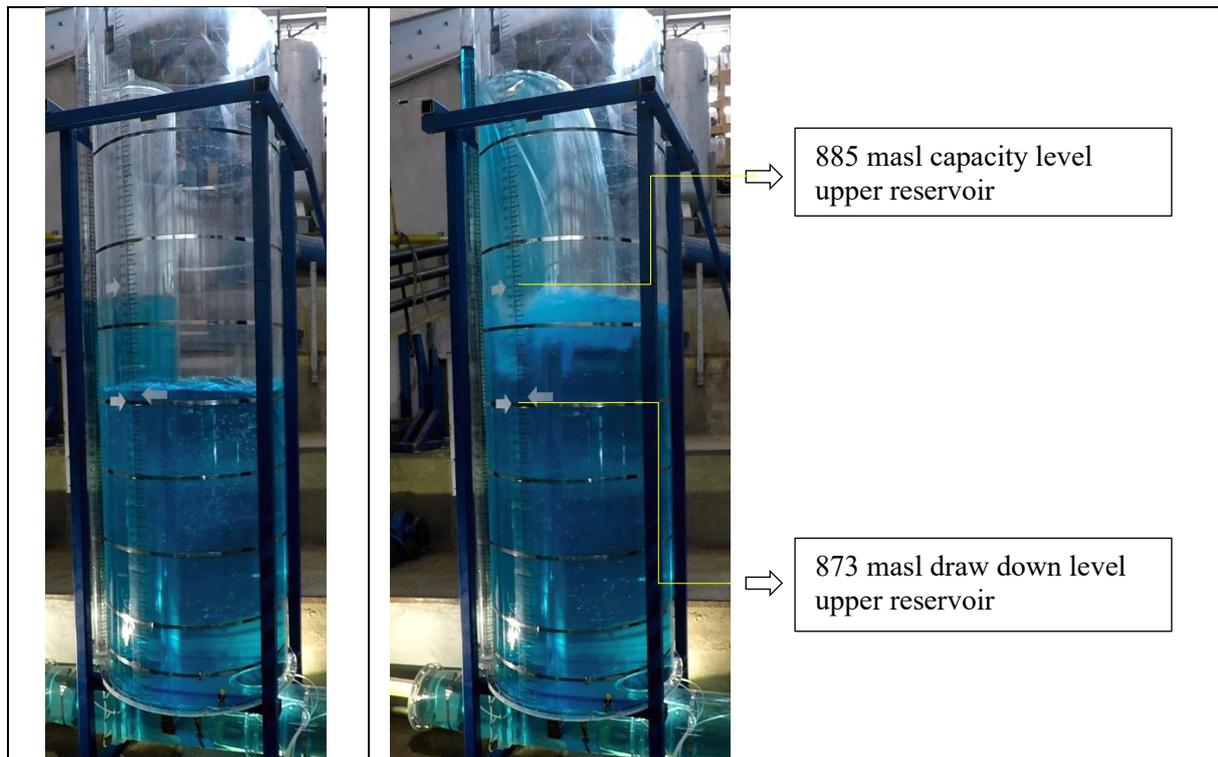


Figure 9. Examples of Gouvães headrace surge tank transient flow achieved during physical transient model tests at TU Graz for the critical exceptional load cases related to upsurge with water fall, starting levels are indicated.

5.3. Tailrace surge tank transient tests key results and optimizations

Figure 10 shows examples of transient flow developing in the Gouvães tailrace surge tank reduced scale model for the most critical exceptional load cases PU4C and TU10, see description in Table 3, where the transient tests allowed to:

- mitigate the fast free surface up-surge wave in the upper expansion chamber that hits the end wall inducing wall shocks and avoiding the spilling above the wall, by i) developing dissipating baffles, see Figure 10 top left, ii) a weir at the chamber inlet, see Figure 10 bottom left, iii) increased slope at the chamber bottom;
- mitigate the risk of air entrainment in the tailrace tunnel by the use of the weir at the upper chamber inlet, see Figure 10 bottom left, which includes an outlet at the bottom that releases smoothly the flow from the upper chamber to the lower chamber and thus prevent from strong air-water flow mixture in the bend before the lower chamber and avoid jet flow pattern at the inlet of the lower chamber, see Figure 10 bottom right (original design), and reduces free surface and slug flows at the ceiling of the lower chamber, see Figure 10 top right;
- improve flow transition between the lower chamber and the inclined gallery during up-surge.

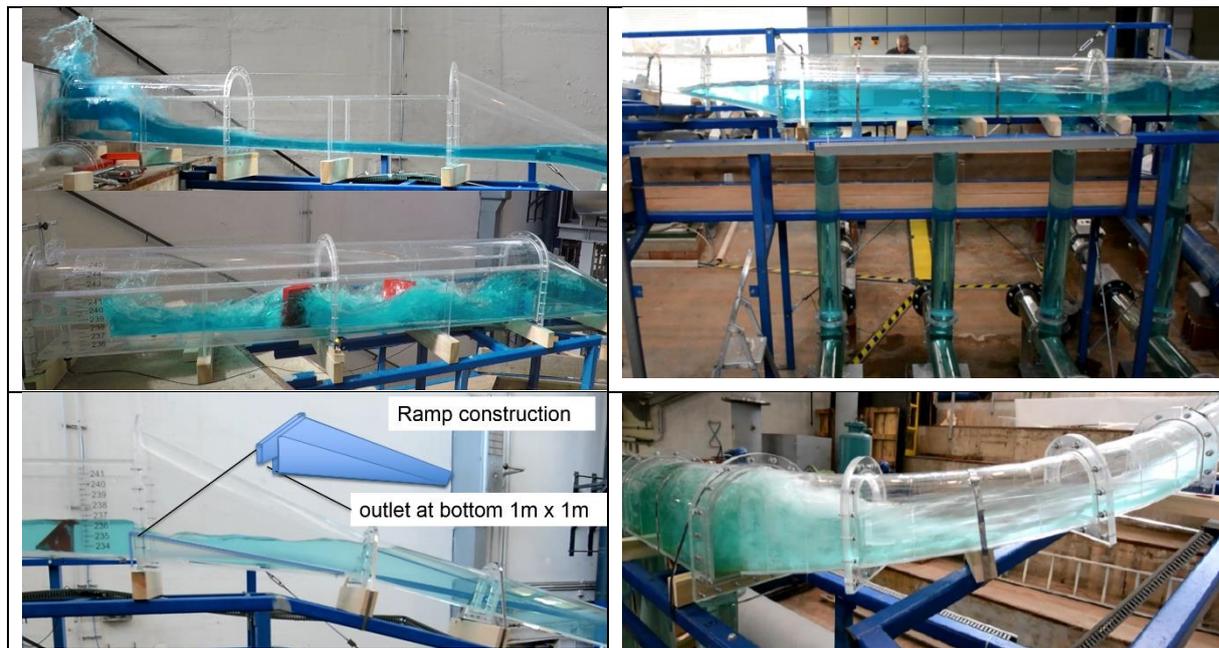


Figure 10. Gouvães tailrace surge tank transient flow achieved during physical transient model tests at TU Graz for the critical exceptional load cases related to up-surge in upper chamber (left) with ramp construction and down surge in the lower chamber and related risk of air entrainment (right), that was significantly mitigated by the ramp construction that creates a retention weir.

6. Conclusions

The hydraulic design of high head pumped-storage power plants such as the 880 MW Gouvães PSPP currently under construction in Portugal and developed by Iberdrola, is a challenging system, concerning the hydraulic transients. The design followed an iterative process that involved all parties that allowed to refine and improve the design at each stage of the project.

The Gouvães PSPP includes a long headrace tunnel, a headrace differential surge tank with integrated safety gate, a long penstock, 4 reversible Francis pump-turbines of very low specific speed, a tailrace differential surge tank and a tailrace tunnel, which overall hydraulic transients needed to be carefully addressed. In this context, the design of both the headrace and the tailrace surge tank are critical to ensure a safe and reliable operation while relying on cost effective solutions. It appeared decisive to consider detailed 1D transient simulation model that includes realistic 4 quadrants characteristics of the low specific speed pump-turbines already at early stage of the project, to properly address critical hydraulic issues strongly influenced and mitigated by the surge tank design for safe operation, such as risk of water column separation in the pump-turbine draft tubes and at the top of the penstock. Along the headrace and tailrace tunnels, as well as the penstock the transient pressure was properly quantified.

At Gouvães PSPP, both the headrace and tailrace surge tanks are of differential types which are efficient solutions to accommodate the mass oscillations. The use of physical transient model tests for both surge tanks was essential to detect possible issues inherent to complex 3D unsteady free surface and two phases flows that develops within the surge tanks and to optimize the design to achieve safe, reliable operation and even saved significant construction costs of the tailrace surge tank due to optimized solution development. The flexibility of Gouvães PSPP with 19 GWh storage capacity will support the Portuguese electrical power network with better integration of large share of new renewable energies.

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