# Benefits of a digital twin during the commissioning of high head 880 MW Gouvães pumped-storage plant

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## Introduction

The 880MW pumped-storage power plant (PSPP) of Gouvães, which is part of the Alto Tâmega hydro power scheme developed by Iberdrola in the North of Portugal, was commissioned in 2022. The hydraulic design of the power plant is challenging with 4 reversible Francis pump-turbines of very low specific speed, a long high-pressure penstock, a differential two shaft headrace surge tank with a differential orifice throttle and a two-chamber tailrace surge tank linked to a 700 meters long tailrace tunnel.

As this strategic pumped-storage power plant is complex, the Hydro-Clone® digital twin, developed by Power Vision Engineering, was implemented in Gouvães PSPP to accurately monitor the transient behavior of the PSPP. A particular focus was put on the water levels in the upstream and downstream surge tanks, as well as the pressures along the waterway during the PSPP commissioning. The Hydro-Clone® system is using the SIMSEN 1D numerical model developed during the PSPP design phase to perform transient analysis in real-time during the site tests. This numerical model was calibrated prior the commissioning by means of available on-site measurements, reduced scale physical transient tests to assess free surface flow in the downstream surge tank and CFD simulations to define the local losses coefficients of the surge tanks.

This paper presents the results of the key transient tests performed during the commissioning to validate the proper hydraulic behavior of the new PSPP and the comparison between 1D simulation results and corresponding site measurements. Moreover, the paper highlights the major advantages of the use of such digital tools for commissioning and the ability to make decisions within minutes of the completion of each site-test.

## 1. Gouvães PSPP description

The hydraulic layout of the 880MW Gouvães pumped-storage power plant, PSPP, is presented in Figure 1. The power plant includes a 4.7km headrace tunnel, a headrace surge tank, a 2.2km penstock, a power house with 4 units, a tailrace surge tank and a tailrace tunnel of 700m. The power house is equipped with ultra-high-head single stage reversible Francis pump-turbines. The rated values of the unit connected to a synchronous generator are provided in Table 1. The guide vane and main-inlet valve, MIV, opening and closing laws were optimized by the pump-turbine supplier.

The headrace surge tank is a differential Johnson surge tank with an 8m diameter gate shaft which can spill into a 21m diameter main riser connected to the headrace tunnel with a throttle, see Figure 2. This design of the surge tank was defined to mitigate uplift forces on the penstock protection gate in case of turbine emergency shutdown. The separation of the gate shaft and the main riser provides a pressure equilibrium at the bottom of the gate and the top of the gate 1. The singular head losses of the headrace surge tank were also 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 2.

The tailrace surge tank is located as close as possible to the machine cavern and is characterized by an upper and a lower surge chamber. The lower chamber connects with four shafts into each draft tube pipe, see Figure 3. This approach has specific advantage for very quick water hammer response and mitigates asymmetric water hammer interferences at delayed load rejection events. This design significantly reduces the risk of water column separation in the pump-turbine's draft tubes, inherent to low specific speed pump-turbine featuring very pronounced S-Shape characteristics, see 4.

The optimizations of the design for the surge tanks were carried out by TU Graz Institute of Hydraulic Engineering and Water Resources Management with hybrid modelling approach, combining 1D transient calculation, 3D CFD and reduced scale physical model tests, 5, 6. 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. These phenomena are not included in 1D transient analysis and remain still challenging to address accurately with 3D unsteady CFD.

All these optimizations and analyses have resulted in a robust design for this PSPP, with the aim of integrating a large proportion of new renewable energies in the Portuguese power grid. Using all the as-built drawings and the characteristic curves supplied by the manufacturer, the 1D SIMSEN model shown in Figure 4 was created for the transient study 7, but also to reproduce in real-time any dynamic behavior of the plant.

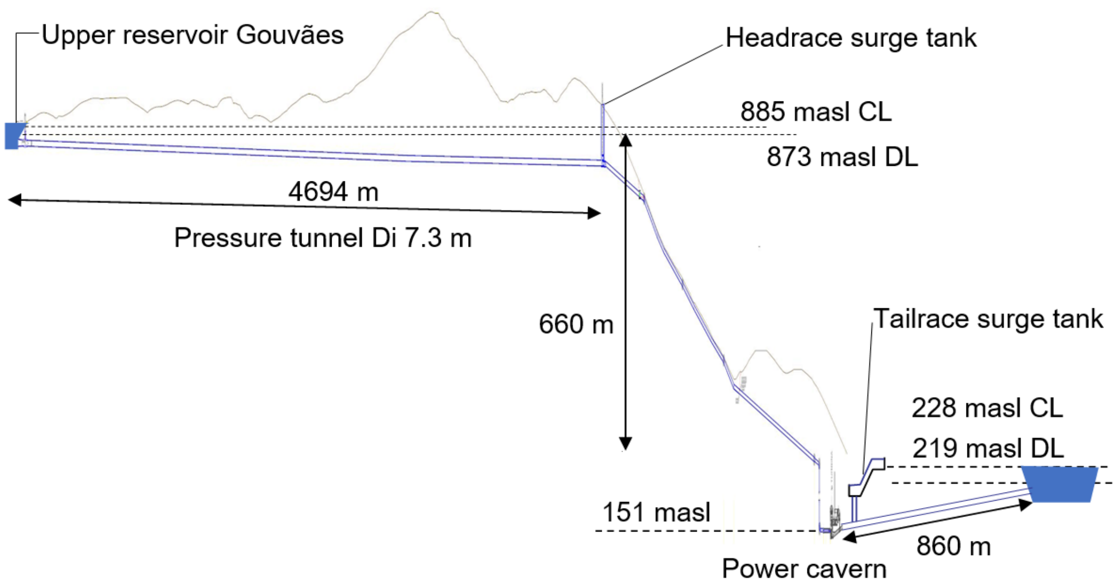


***Figure 1***. *Waterway layout of the Gouvães 880 MW PSPP.*

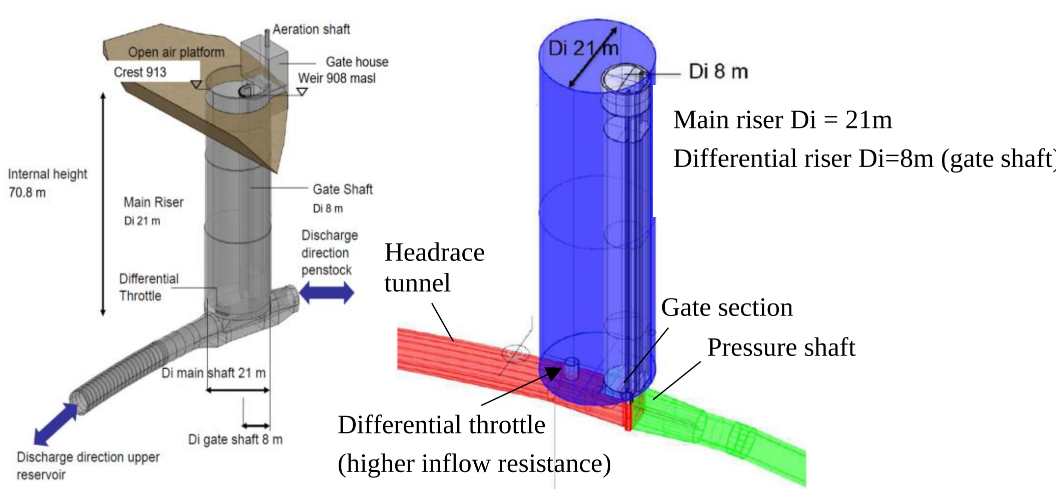


***Figure 2***. *Layout of headrace differential surge tank of the Gouvães PSPP.*

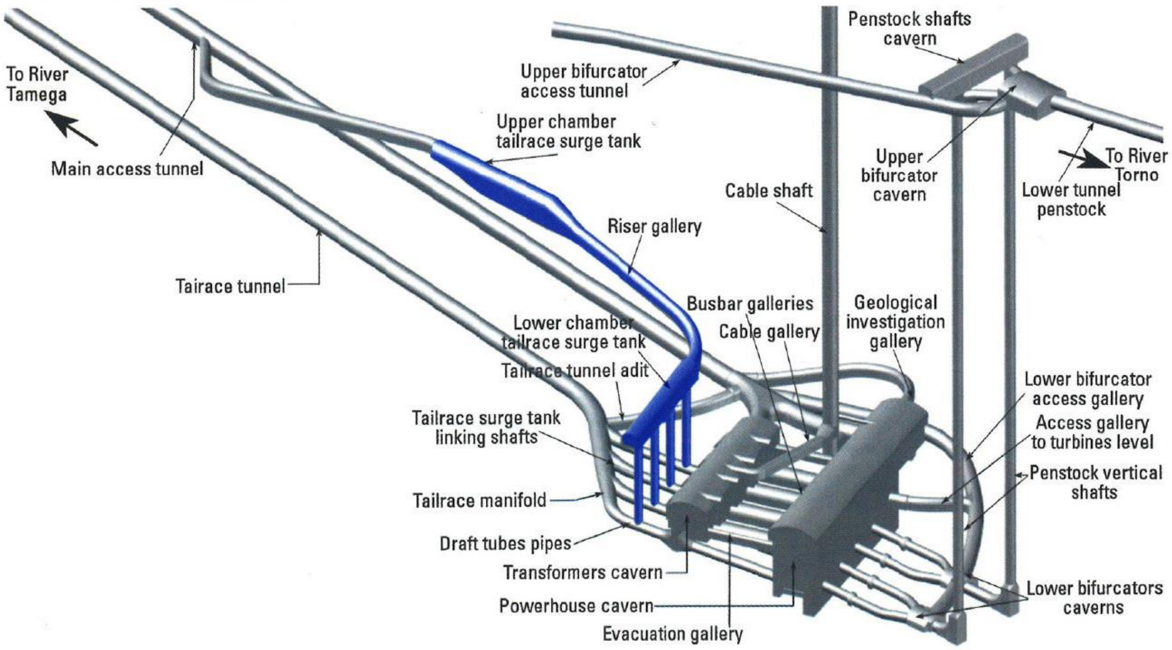


***Figure 3***. *Layout of the underground powerhouse of the Gouvães PSPP and tailrace surge tank (in blue) and related access tunnels.*

***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 |

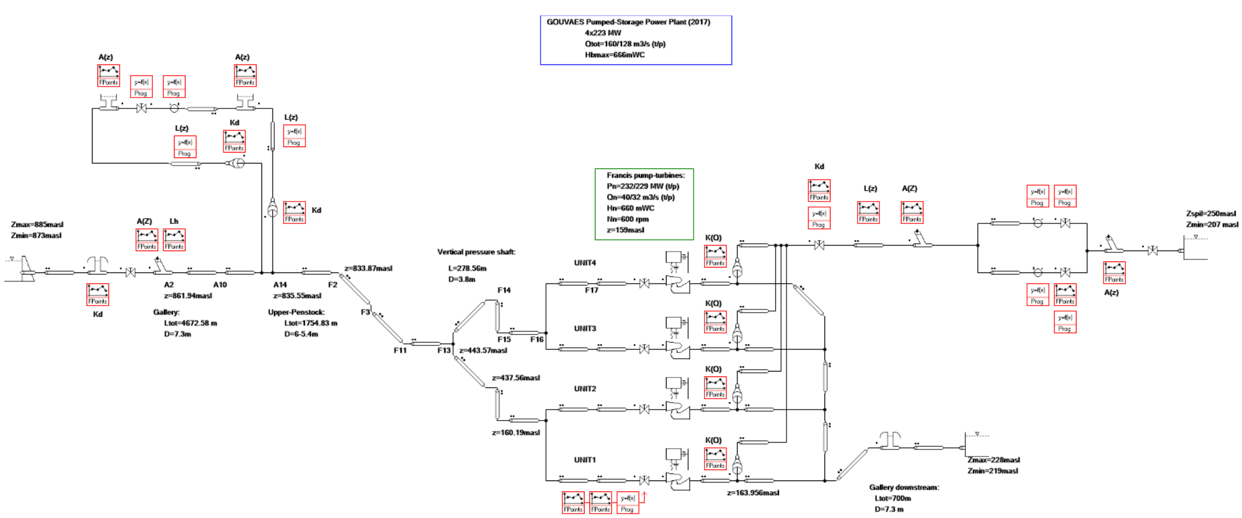

***Figure 4***. *SIMSEN model of the underground powerhouse of the Gouvães PSPP.*

## 2. Real-time monitoring with Hydro-Clone®

Hydro-Clone® is an innovative Real-Time Monitoring System (RTSM) based on a calibrated and validated digital model of the hydropower plant capable of reproducing in real-time any dynamic behavior of the plant based on the boundary conditions measured in situ 7, 9, 10. This comprises the data exchanged between the Hydro-Clone® computer and the HPP SCADA system at a sampling of 10Hz using the MODBUS TCP protocol, as well as eventual additional signals coming from other programmable logic controllers (PLC) with higher sampling frequency for the pressure signals, dispatched in powerplant, 11.

This system allows continuous diagnosis of the health of a hydro power plant (HPP) by digital cloning of the main hydraulic and electrical components of the plant using SIMSEN software. The immediate benefit of this digitalization is that it allows to evaluate non-measured and non-measurable quantities, such as pressures throughout the water conduits, to be monitored at any time without the physical installation of additional sensor 12. A custom-built archival storage system and an associated database allow for the display and analysis of previous results. As such, the digital twin can identify unusual events, for which measurements and simulations are no longer in agreement. This can be used to detect a sensor failure, but also potentially more serious events such as unintentional water hammer caused by an improper turbine shutdown sequence.

## 3. Calibration of the SIMSEN model

Given the complexity of this layout, particularly for the tailrace surge tank, there may be discrepancies between the as-built drawings and the actual design. Consequently, a calibration of the numerical model developed during the design phase is necessary before commissioning with available first on-site measurements. The small corrections to the SIMSEN model are described in the following sections.

### 3.1 Headrace surge tank

The first comparisons for the water levels in the main riser and in the gate shaft revealed a small difference in mass oscillation, see Figure 5. The phenomenon of mass oscillation is slow, and it is important to reproduce the phase and amplitude correctly to ensure the right pressure level in the pressure shaft during events such as an emergency shutdown of one or more units. To correct the mass oscillation, the cross-section area was multiplied by a factor 1.02, compared to the drawings, corresponding to 1% difference on the diameter value. With a filter of 10s applied to the simulation results, to account for site measurement filtering, a perfect match is obtained, see Figure 6.

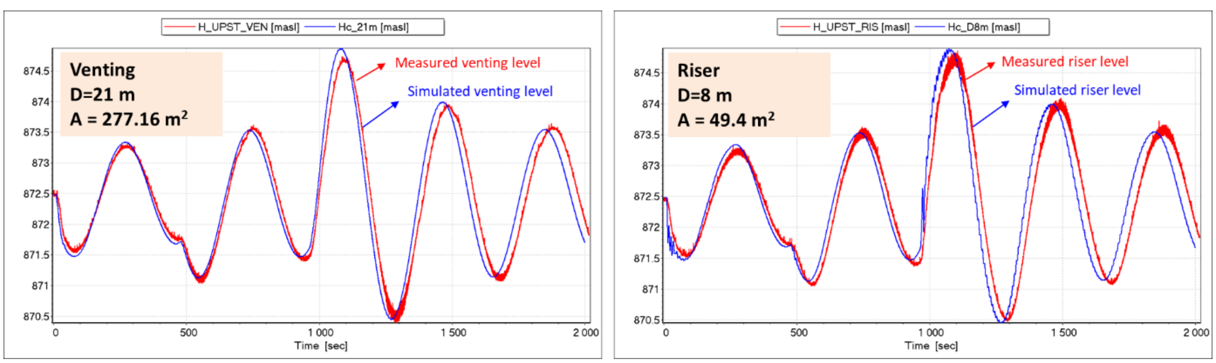


*Figure 5. Comparison of the water level in the main riser (left) and in the gate shaft (right) between the site-measurement (red line) and the SIMSEN model before the calibration (blue line) [masl].*

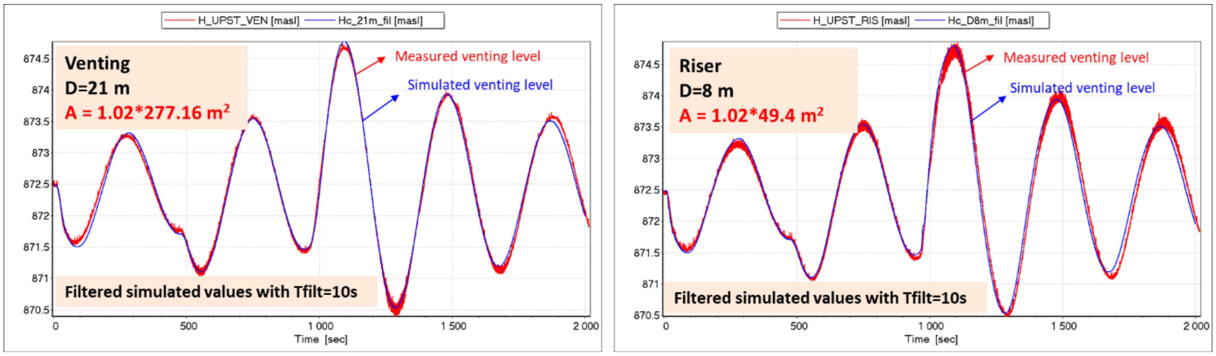


*Figure 6. Comparison of the water level in the main riser (left) and in the gate shaft (right) between the site-measurement (red line) and the SIMSEN model after the calibration (blue line) [masl].*

### 3.2 Tailrace surge tank

For the downstream surge tank, it is more difficult to compare the measurement with the numerical model. Indeed, the only pressure sensor is located in the upper chamber at an elevation of 231masl. Consequently, if the water level does not reach this elevation, it is not possible to validate the dynamic behavior of the downstream surge shaft. Consequently, the static pressure in the draft tube was used as a reference to validate mass oscillation in the downstream section.

To calibrate the amplitude and phase of mass oscillation, the friction factor in the tailrace tunnel was reduced from $\lambda$=0.0128- to $\lambda$=0.01-. Moreover, for the downstream gate shaft, the loss coefficient $K_d$ was increased with a factor of 4. This value influences the damping of the mass oscillation in the downstream part. This modification required a slight correction of the horizontal cross section area of the downstream riser from 49.5m$^2$ to 50m$^2$ to re-phase the downstream mass oscillation with the measurement.

After these small modifications, the static pressure in the draft tube is well reproduced in the SIMSEN model with the correct phase, and the water level seen by the sensor in the upper chamber is also well reproduced, see Figure 7 and Figure 8. This comparison highlights the importance of having a real-time numerical model to be able to know at any time the pressure in difficult access location such as surge shafts, etc.

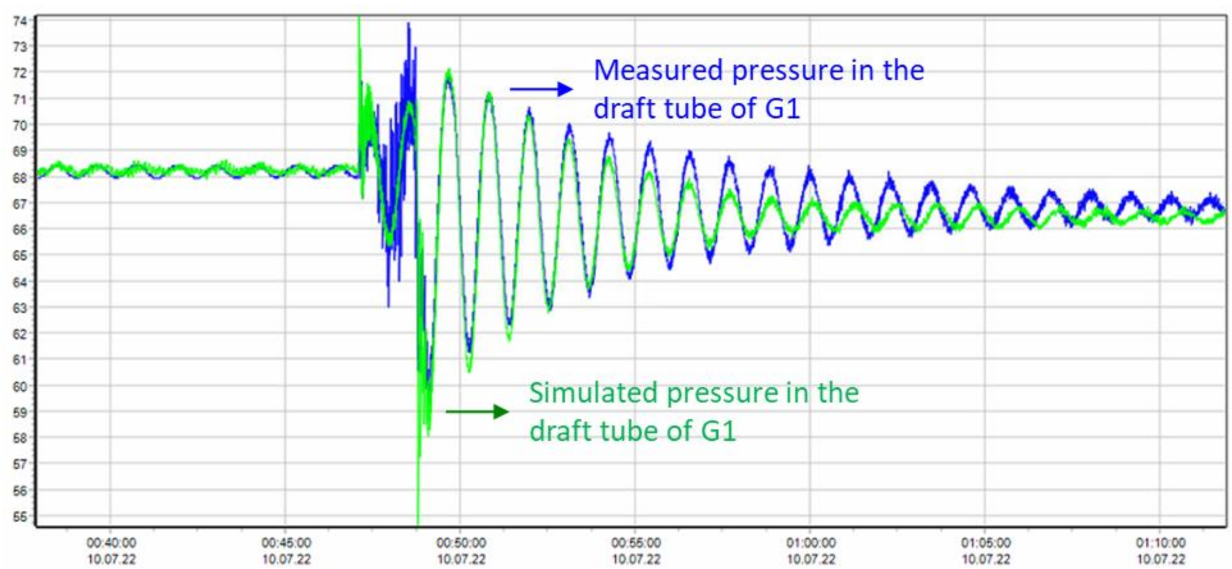


*Figure 7: Comparison of the static pressure in the draft tube for unit U1 between the site-measurement (blue line) and the SIMSEN model after the calibration (green line) [mWC].*

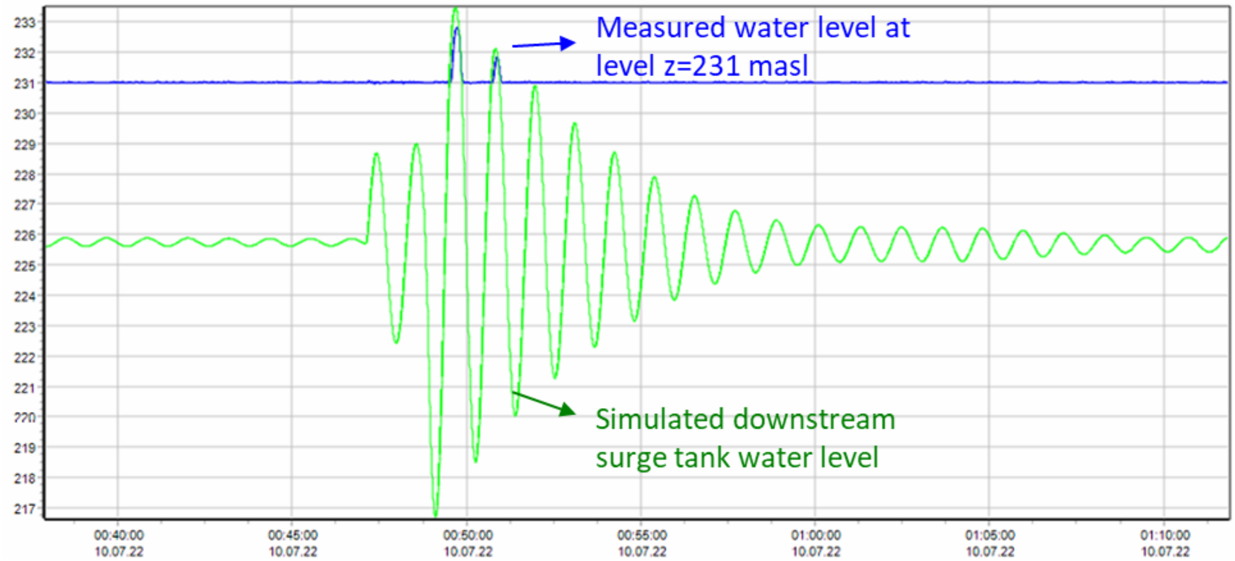

*Figure 8: Comparison of the water level in the downstream surge tank between the site-measurement (blue line) and the SIMSEN model after the calibration (green line) [masl].*

This calibration with on-site measurement highlights the need to add an uncertainty margin during the transient study. Usually, an uncertainty margin of 10% is applied during a transient study for extreme pressures obtained in the spiral case, the draft tube or water levels in surge tanks. This uncertainty margin can be reduced to 5% if the SIMSEN model has been calibrated with on-site measurements to take account of 3D flow effects.

After this calibration of the SIMSEN model, the simulation results faithfully reproduced the site-measurements and this Real-Time Monitoring System can become a real asset during the commissioning phase.

## 4. Results of commissioning campaign

With the Hydro-Clone® software, the pressures all along the waterway and water levels in the surge tanks can be analyzes in real-time. During the commissioning campaign, after checking that the extreme pressures are within the admissible values, a technical report was prepared to document the test. Then, a test at higher power could be carried out. In the end, thanks to the Hydro-Clone® software, only 2 days were necessary to perform and validate hydraulic transient test of this complex 880MW PSPP in pump and turbine mode.

The commissioning of the 4 units in turbine mode and in pump mode was carried out on July 20-21, 2022. Among the different tests, the emergency shutdown of the 4 units in turbine mode is documented in this chapter. For this load case, the following points were noted:

- The speed deceleration differs between units U1-U3-U4 and unit U2, see Figure 9. This difference is explained by a different closing law for the unit U2. During this sequence, the unit U2 was forced to perform a hydraulic closing with a slow ramp and Hydro-Clone® software was perfectly capable of detecting this accidental situation. Moreover, thanks to Hydro-Clone® software, it was easy to check that all admissible limits had been respected during this particular sequence, including all the pressure along the entire penstock.
- The amplitude of the water hammer is well reproduced by the SIMSEN model, see Figure 10. The measurement feature however some significant high frequency pressure fluctuations induced by the reversible pump-turbine itself which are not simulated by 1D models, as already reported in other pump storage power plant 13. These pressure fluctuations result from the pump-turbine internal unsteady flow field (rotor-stator interaction, rotating stall, vortex rope, stochastic flow, etc). In the transient study, the pressure fluctuation margin is estimated at 10% of the unit runner peripherical velocity head for the pump-turbine high pressure manifold and at 3% for the pump-turbine low pressure manifold.
- The transient draft tube pressure is well reproduced by the numerical model, see Figure 11.

- The headrace surge tank water level amplitudes are in accordance between measurements and simulation, see Figure 12. A saturation of the pressure sensor during several minutes in the gate shaft (D=8m) part is observed. The SIMSEN model in real time was able to indicate the transient behavior of the water level in the riser during the period when the sensor was saturated. The maximal water level is equal to 908.6masl and a small volume spilled in the main riser (D=21m) part of the headrace surge tank. The head difference of the two shafts is governed by the differential throttle providing a significant higher loss at surge tank filling as for emptying.
- For the tailrace surge tank, the highest water levels are still in phase with the measurement, see Figure 13. According to the pressure sensor fixed in the upper chamber, the maximum water level is 1.3m lower in the measurement (234.2masl) than in the simulation (235.5masl). The SIMSEN model is therefore more conservative for this quantity and this difference highlights the need to add an uncertainty margin to the simulation results of the transient study.
- Overall, the qualitative time evolution of the quantities compared between the measurements and the simulation shows a good agreement. The pressure envelope shown in Figure 14 indicates that the pressure along the waterway is below the pressure limitations. There is no danger of overpressure for this load case.

Finally, the Hydro-Clone® software during this load case is an excellent tool for quickly determining if a closing law is different for one of the units, or if a pressure sensor saturates for a few seconds. These types of unforeseen events are highly likely to occur during commissioning of such a complex power plant, and the use of a digital clone ensures a continuous diagnosis of the health of the power plant at all times, reinforcing the security of the commissioning.

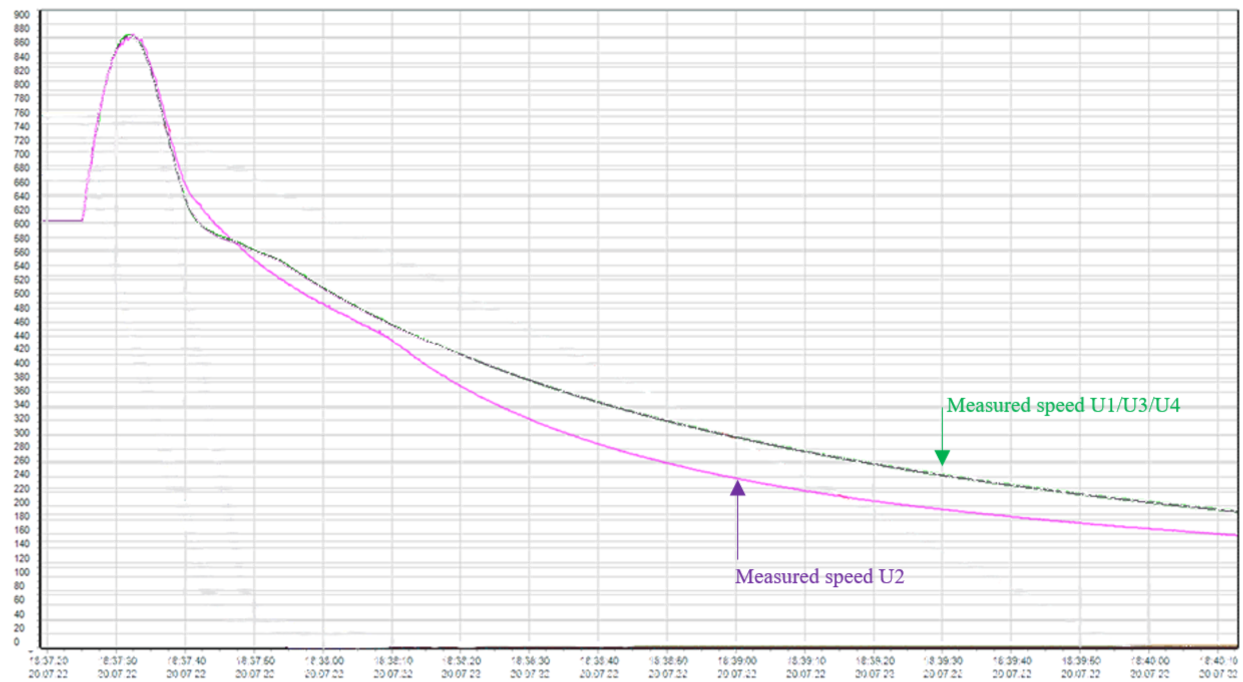


***Figure 9*** *Rotational speed of all units on the left axis [rpm].*

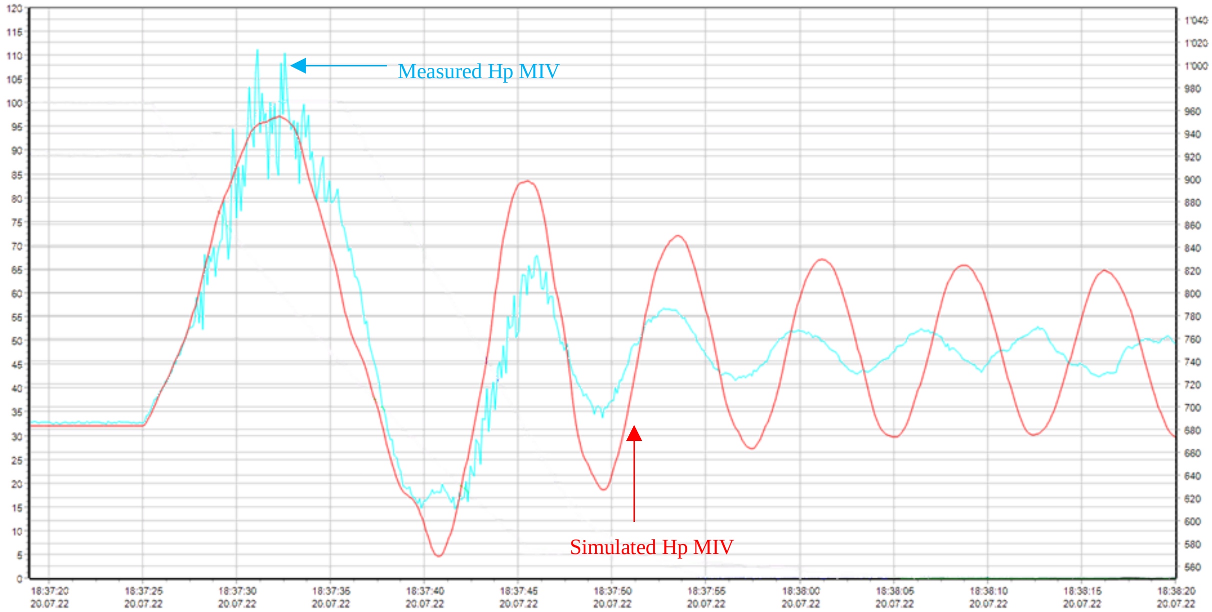


***Figure 10*** *Pressure head at upstream MIV of the unit U1 on the right axis [mWC].*

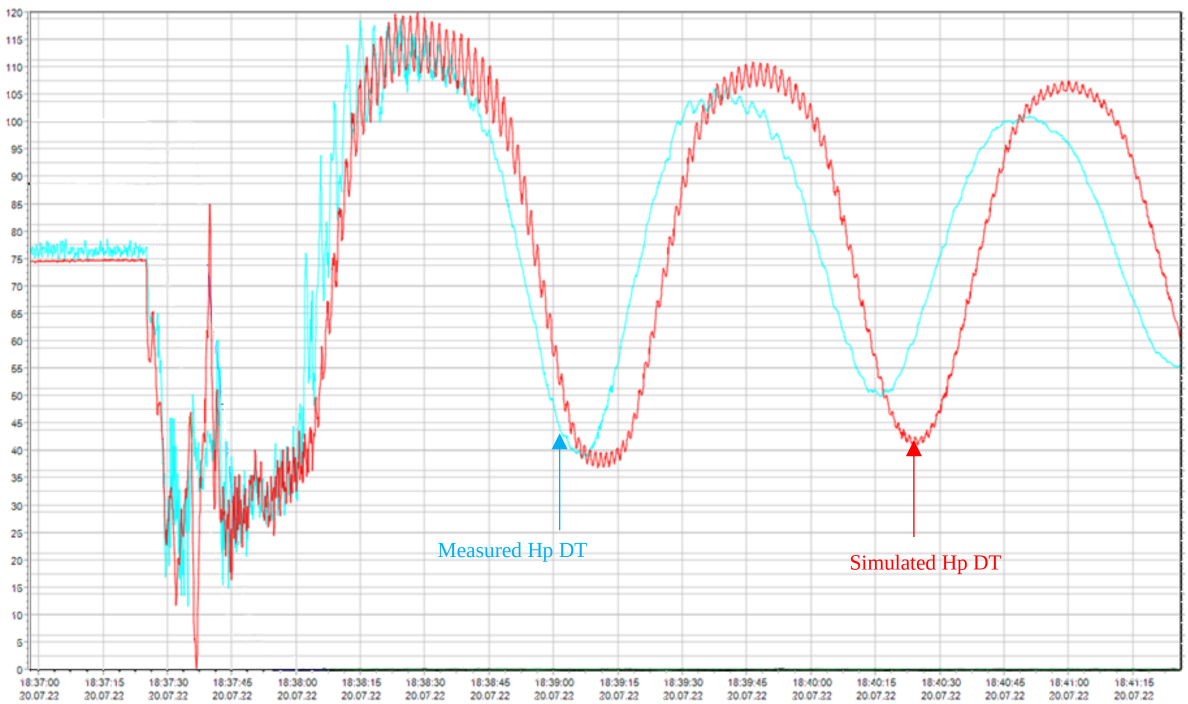


***Figure 11*** *Pressure head in the draft tube of the unit U1 on the right axis [mWC].*

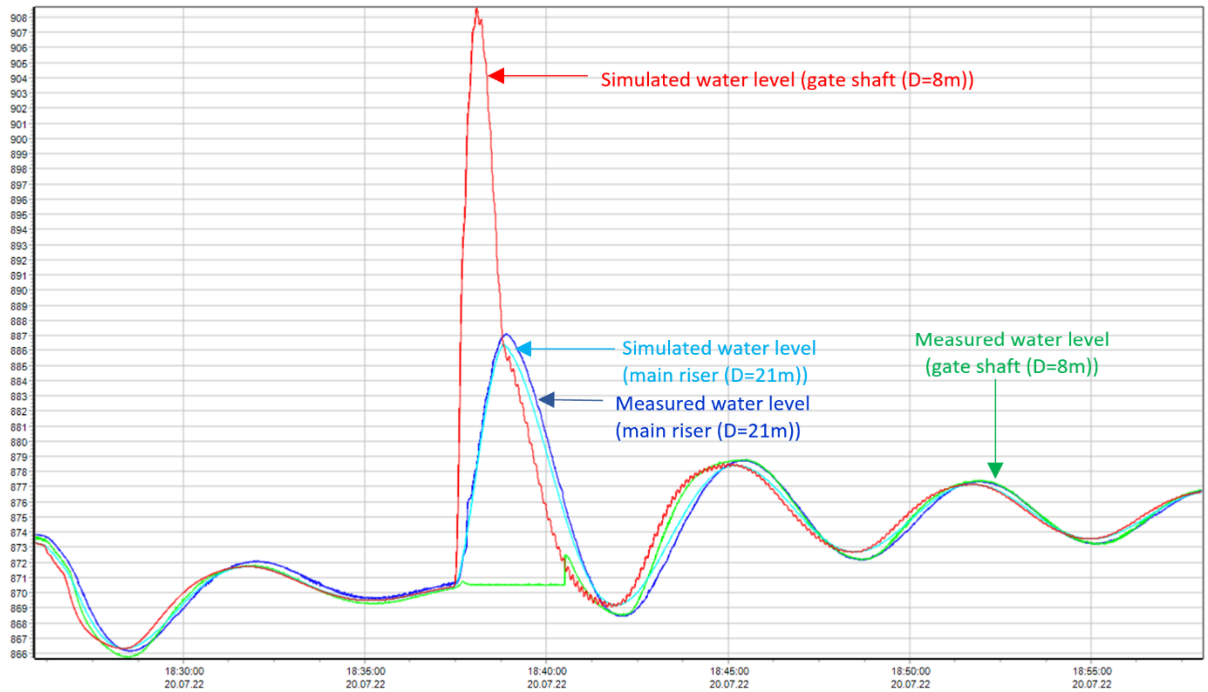


***Figure 12*** *Headrace surge tank water levels (gate shaft (D=8m) and main riser (D=21m)) [masl].*

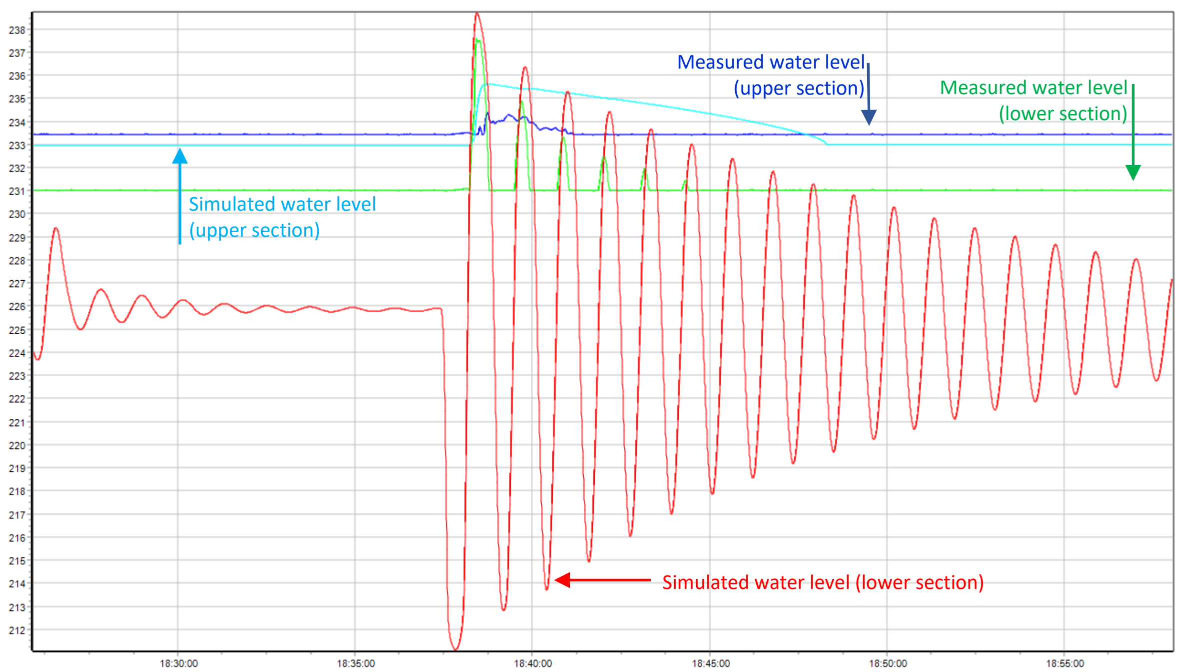


***Figure 13*** *Tailrace surge tank water levels [masl].*

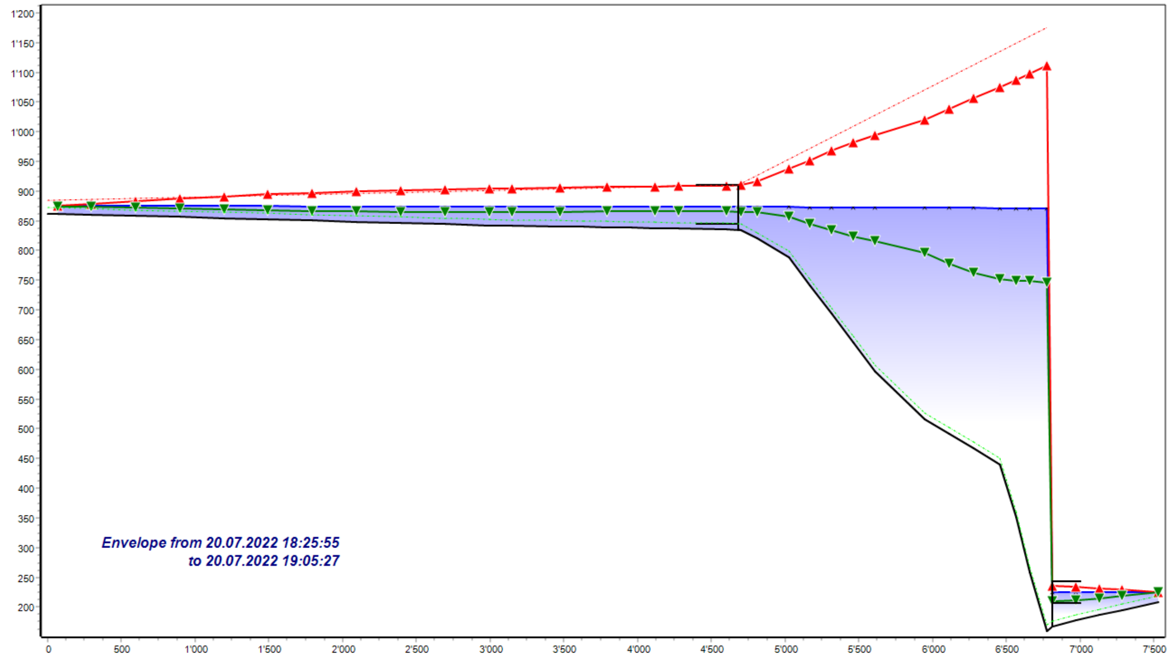


***Figure 14*** *Pressure envelope of the piezometric head along the layout of Gouvães (penstock with units U1/U2) [masl].*

## 5. Conclusion

The Gouvães PSPP is a strategic pumped-storage power plant with the aim of integrating a large proportion of new renewable energies in the Portuguese power grid. The hydraulic design of the power plant is challenging with 4 reversible Francis pump-turbines of very low specific speed, a long high-pressure penstock, a differential two-shaft headrace surge tank with a differential orifice throttle and a two-chamber tailrace surge tank linked to a 700 meters long tailrace tunnel. This complex design was modeled using SIMSEN software, and the 1D model was calibrated with on-site measurements.

For the commissioning phase, the Hydro-Clone® digital twin was deployed to accurately monitor the transient behavior of the PSPP. The use of this digital clone ensured a continuous diagnosis of the health of the power plant at all times, reinforcing the security of the commissioning. For instance, during the emergency shutdown of the 4 units in turbine mode, the closing law of the U2 unit was forced to perform a hydraulic closing with a slow ramp and Hydro-Clone® software was perfectly capable of detecting this accidental situation. Moreover, despite a sensor saturation in the riser during several minutes, the SIMSEN model in real time was able to indicate the transient behavior of the water level in the headrace surge tank. The real-time numerical model is also an advantage in the tailrace surge tank where only one pressure sensor is present in the upper chamber given the difficult access location. The digital twin indicates the water level in this surge tank at any given moment.

Finally, during the commissioning campaign of this high-head 880 MW PSPP, thanks to the Hydro-Clone® software, a technical report was prepared after each load case with a summary of the extreme pressures along the waterway, the water elevation in the surge tanks and the verification of the respect of the admissible values. After the validation of this report, a test at higher power could be carried out. In the end, only 2 days were necessary to perform multi-units hydraulic transient tests from 220 MW to 880 MW total capacity of this complex PSPP in pump and turbine mode.

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