REAL-TIME HYDRAULIC TRANSIENT MONITORING AT GRAND'MAISON PSPP WITH THE HYDRO-CLONE DIGITAL TWIN

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Abstract

The Grand'Maison pumped-storage power plant (PSPP), one of the largest facilities of its kind in Europe, plays a crucial role in grid stability through its high operational flexibility, enabled by a combination of 4 Pelton turbines and 8 reversible pump-turbines. This flexibility, however, results in frequent and complex hydraulic transients that challenge the plant's extensive waterway system. To improve monitoring and ensure operational safety, the Hydro-Clone digital twin solution, which is based the real-time simulation of a SIMSEN model of the power plant, was deployed at Grand'Maison. This advanced tool delivers real-time insights into transient hydraulic behavior. The paper presents the deployment and integration of Hydro-Clone, including solutions to key technical challenges such as the absence of direct measurements for the spherical valve positions on reversible units. Several examples are discussed to demonstrate the system's effectiveness, such as maintaining monitoring continuity during sensor failures, improving transient diagnostics during hydraulic short-circuit operations, and supporting the recommissioning of units through dynamic behavior validation. These results underline the operational value and benefits of digital twin technologies for real-time hydraulic transient monitoring in large-scale hydropower systems.

1. Introduction

With more intermittent renewables on the grid, pumped-storage plants play an increasingly critical role in maintaining stability. Among various strategies to enhance their contribution to ancillary services, the hydraulic short-circuit (HSC) operating mode has emerged as a cost-effective and flexible option to modulate the pumping power of plants equipped with fixed-speed units. However, this mode introduces new hydraulic transients that must be carefully assessed to ensure safe and reliable operation.

At Grand'Maison pumped-storage power plant, one of Europe's largest facilities, the feasibility and risks of HSC operation were thoroughly investigated in the framework of the XFLEX HYDRO project [1][2]. That work confirmed the potential of HSC but also highlighted the importance of precise monitoring tools capable of capturing fast, site-specific transient phenomena.

In this context, the Hydro-Clone, a digital twin solution that enables real-time simulation and monitoring of hydraulic transients based on a calibrated SIMSEN model of the power plant, was deployed at Grand'Maison. This paper presents the implementation and integration of Hydro-Clone, its adaptation to local constraints, and its operational use in several key scenarios. These include monitoring during sensor failures, transient analysis of HSC events, and support for recommissioning processes, demonstrating the growing value of real-time digital twins in complex hydropower environment

2. The Grand'Maison PSPP

Located in the French Alps, Grand'Maison is the largest pumped-storage power plant in Europe, with a generating capacity of 1'800 MW and a pumping capacity of 1'240 MW. Commissioned in 1986, it plays a strategic role in the French electricity system by providing fast and flexible support for frequency regulation, peak load management, and other ancillary services.

The plant features 12 hydroelectric units split between two powerhouses. The main characteristics of these units are defined in the Table 1. The surface powerhouse contains four Pelton turbine units (G9–G12), each originally rated at 156 MW but in the process of being upgraded with 170 MW units. The underground powerhouse, located 50 meters below ground level, houses eight fixed-speed reversible Francis pump-turbine units (G1–G8). These units are distributed across three pressure shafts, each supplying both turbine types, see Figure 1.

Table 1. Main hydraulic characteristics of Grand'Maison PSPP

Type of turbine	Pelton turbine with 5 injectors	Reversible Francis pump-turbine (4 stages)
Number of units	4 (G9-G12)	8 (G1-G8)
Head	Min 817.4 mWC; Max 922.4 mWC	Min 821.5 mWC; Max 955.0 mWC
Configuration	1–2–1 per shaft	3–2–3 per shaft
Rated rotational speed	428 min-1	600 min-1
Rated mechanical power	156 MW (upgrade in process to 170 MW)	156 MW

The hydraulic layout comprises nearly 9 km of waterways, including a 7 km headrace tunnel, a surge tank with a 10 m diameter vertical shaft of 185 m and a differential expansion chamber at the top with a surface area of 1,640 m², as well as three 1.5 km long penstocks supplying the units. The water is stored between two reservoirs: the upper Grand'Maison reservoir (150 million m³) and the lower Le Verney reservoir (15 million m³). The lower reservoir limits the duration of continuous operation to approximately 30 hours in pumping mode or 20 hours in generating mode at full power.

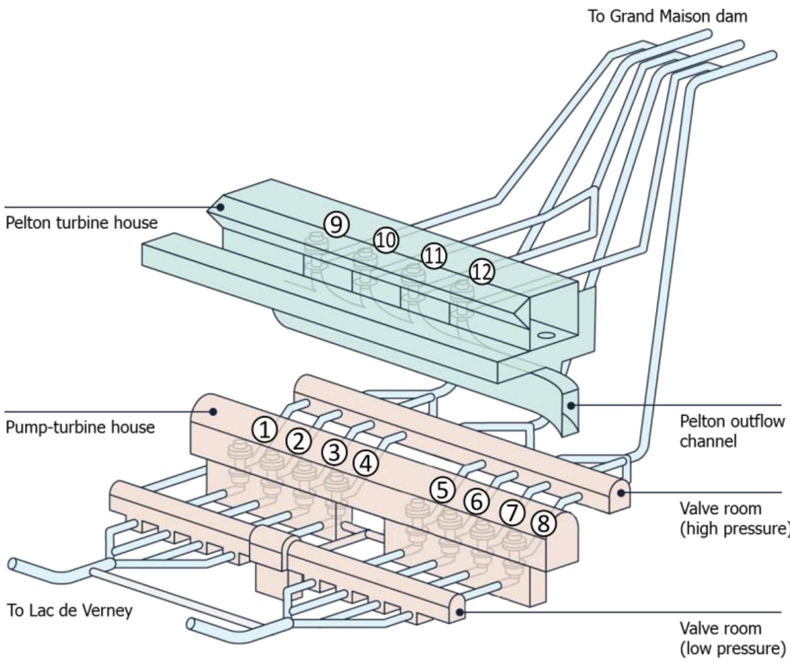

Figure 1. Configuration of the Grand'Maison pumped storage power plant.

3. The Hydro-Clone Digital Twin

3.1 Concept and Methodology

Hydro-Clone® is a digital twin solution designed to monitor in real-time transient hydraulic phenomena in hydropower plants. It is based on a physics-based 1D simulation model developed with SIMSEN, which accurately replicates the dynamic behavior of the hydropower plant [3][4][5]. The system continuously receives real-time boundary conditions from the power plant, such as injector opening, valve state and reservoir water levels, which are injected into the SIMSEN model at a frequency of 10 Hz. Simulations are executed on a dedicated on-site PC, and results are stored in an tailor-made database system that enables archiving, visualization, and retrospective analysis of transient events.

Hydro-Clone operates as a real-time simulation monitoring system, comparing simulated outputs with live measurements to detect discrepancies. This enables early identification of abnormal behavior, supports diagnostics, and enhances decision-making during critical events. Additionally, by acting as a network of "virtual sensors", the system provides continuous access to non-measured or non-measurable quantities, such as pressure profiles and discharge along the waterways [6][7]. These digital indicators offer valuable insight into the plant's hydraulic state without the need for additional physical instrumentation.

3.2 Implementation at Grand'Maison

A detailed 1D SIMSEN model of the Grand'Maison PSPP was developed and calibrated to reflect the plant's specific hydraulic configuration. The model includes all major hydraulic components, such as the headrace tunnel, surge tank, penstocks, units, and associated valves, see [2] for the implementation detail. Particular attention was given to the modeling of the spherical valves and their service seals, which are represented as two parallel valves, parameterized using characteristic curves provided by the manufacturer. The dynamic behavior of both the pump-turbines and Pelton turbines is also modeled using manufacturer-supplied performance curves, ensuring accurate representation of their response during transient events.

Given the complexity and size of the Grand'Maison PSPP, with 12 units distributed across three pressure shafts, a total of 192 signals were identified to provide the real-time boundary conditions required for Hydro-Clone simulation and monitoring. These signals serve as inputs for both dynamic simulation and real-time comparison with plant measurements. Figure 2 illustrates the corresponding Grand'Maison SIMSEN model with the imposed boundary conditions. One notable challenge during implementation was the lack of continuous measurements for the spherical valve positions, as only end-of-stroke Boolean signals are available. To address this, the valve opening in the real-time simulation is managed using predefined actuation sequences triggered by the state of the end-of-stroke signals. A dedicated logic was implemented in the model to select the appropriate sequence depending on the operational context—whether the unit is starting up in pump or turbine mode, or shutting down—since the valve kinematics differ for each case.

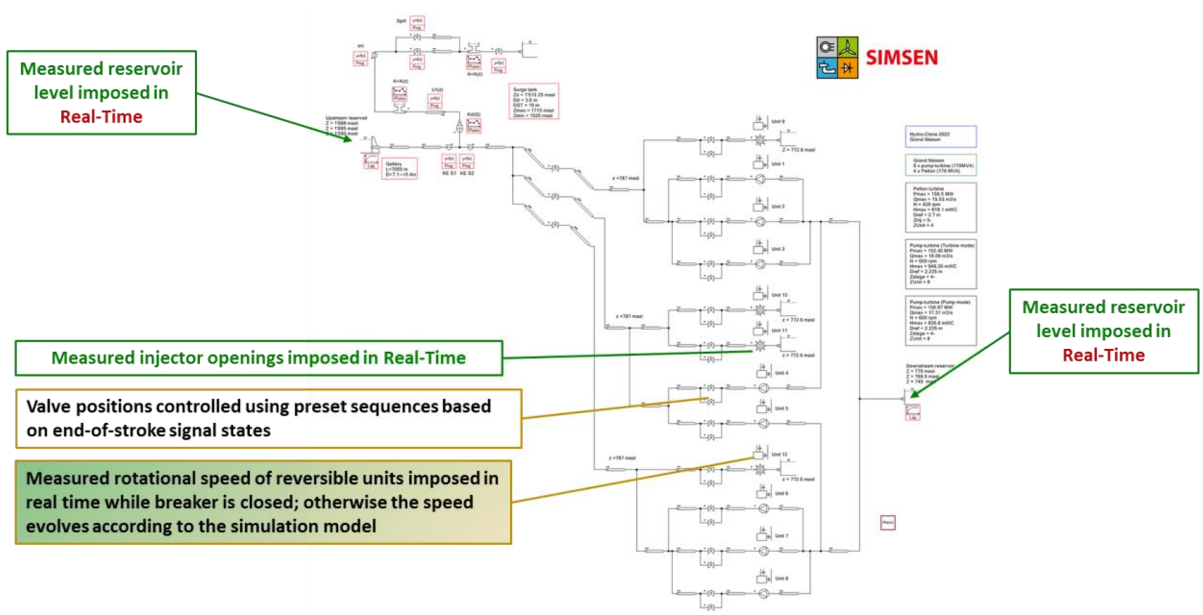

Figure 2. Grand'Maison Simsen model and boundary conditions imposed for real-time simulation.

From an implementation standpoint, all required signals are duplicated and routed as analog inputs into a dedicated PLC, which acts as the interface between the power plant and the Hydro-Clone system. This PLC then manages communication with the Hydro-Clone PC over a separate Modbus TCP network, as illustrated in Figure 3. As such, the Hydro-Clone PC is fully isolated from the main power plant control system and connected to a dedicated internet network with restricted remote access through a firewall. This architecture ensures a high level of cybersecurity: even in the event of a cyberattack, the breach would be limited to the Hydro-Clone PC, with no access to the rest of the plant infrastructure.

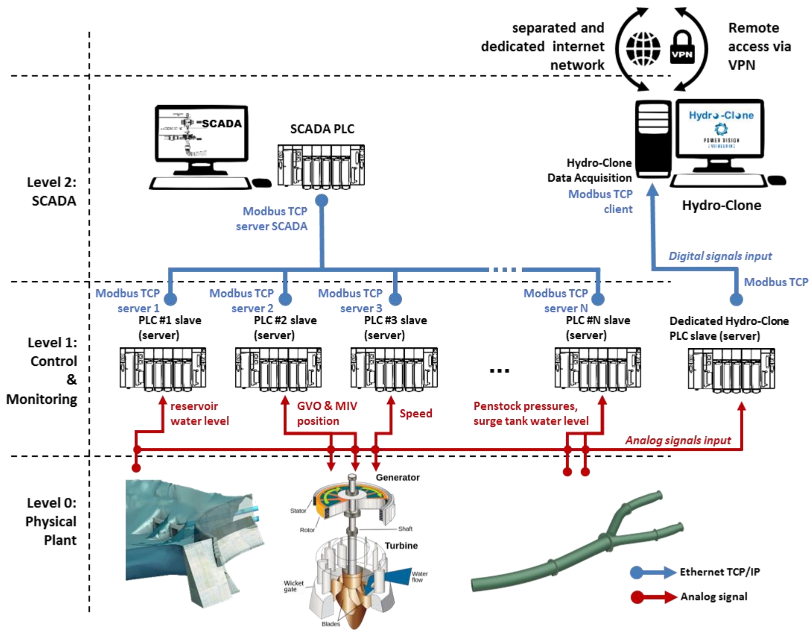

Figure 3. Network architecture of Modbus TCP data exchange implemented at Grand'Maison.

The Hydro-Clone system was deployed in two steps: the configuration for acquiring and recording the signals was completed in November 2021, and real-time simulation was activated in February 2022. Figure 4 shows the Hydro-Clone interface developed for Grand'Maison PSPP, combining a synoptic view of the plant layout with real-time data displays. Instantaneous values of both measured and simulated signals are shown directly on the diagram, while historical trends, such as surge tank water level and penstock discharge, can be explored through time series plots. The interface also provides a live visualization of the piezometric head along the waterway, enabling operators to monitor simulated pressure profiles that are not directly measurable. Additionally, archived data allow for quick access to daily or custom-period pressure envelopes, facilitating the assessment of transient loading patterns and structural stress over time. This interface enables operators to quickly assess system behavior, compare simulation accuracy, and review transient events stored in the database.

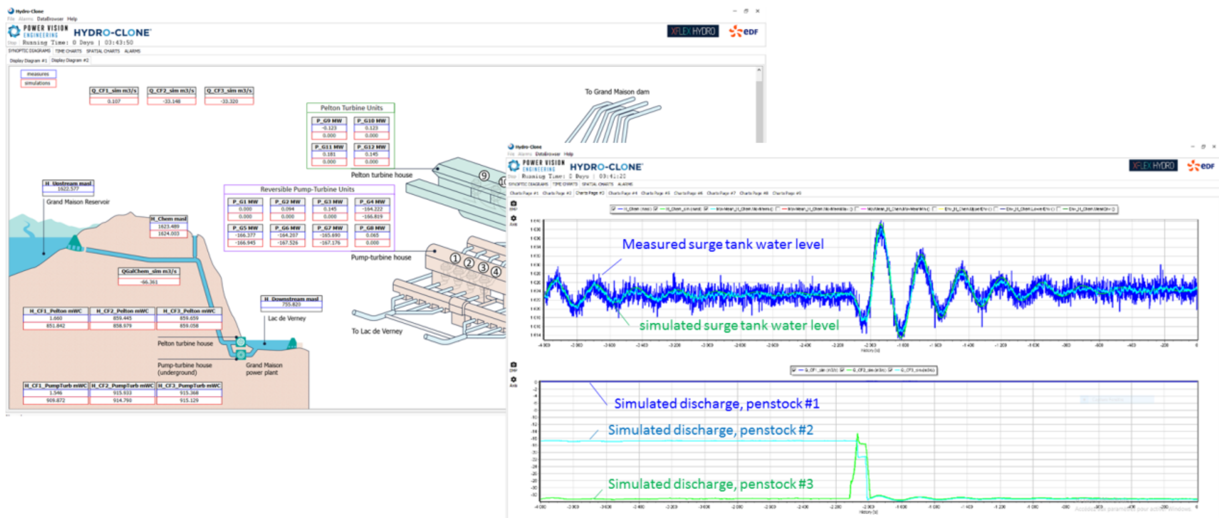

Figure 4. Screenshot of the Hydro-Clone interface at Grand'Maison, showing the plant synoptic with real-time data and historical trends for surge tank level and penstock discharge

4. Case Studies and Operational Results

4.1 Hydraulic Short-Circuit Operation Monitoring

Hydro-Clone was used extensively to monitor and validate the implementation of the hydraulic short-circuit (HSC) operating mode at Grand'Maison. By comparing real-time simulation results with measured signals, the system helped confirm that the introduction of HSC did not lead to new hydraulic instabilities. For instance, Figure 5 illustrates the power output of the units in the configuration 3PT/2PE/3PT , where three pump-turbines operate in pump mode in shafts 1 and 3, and two Pelton turbines generate in shaft 2. In this configuration, Hydro-Clone enabled a detailed comparison of predicted and measured pressure fluctuations, confirming that HSC operation did not induce any unexpected unsteady behavior in the surge tank water level or injector response. This helped to validate the safety and stability of the new operating mode under real grid conditions.

In addition, Hydro-Clone was also used to monitor dynamic sequences involving on-the-fly recoveries, a new capability enabled by HSC operation. In this sequence, when a Pelton turbine is used to launch a pump in a back-to-back configuration, the Pelton can then be synchronized directly to the grid and begin generating without interruption, which is an example of the enhanced flexibility and responsiveness enabled by HSC mode.

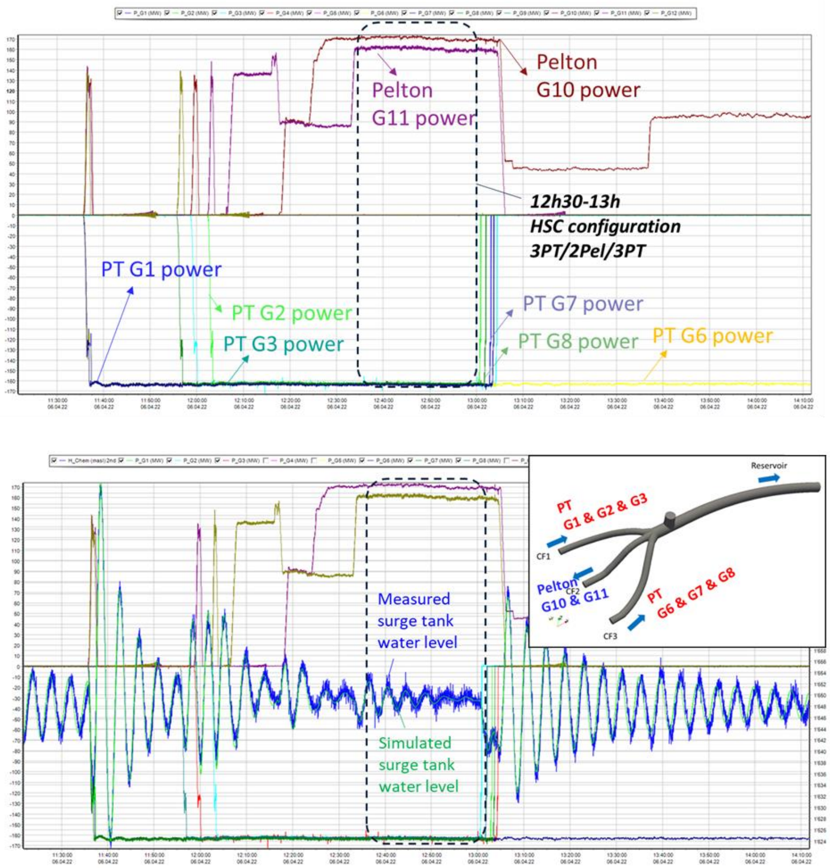

Figure 5. Unit power (measured) and surge tank water level (measured and simulated) during HSC operation at Grand'Maison.

4.2 Sensor Failure Detection and Virtual Monitoring

One of the key benefits of deploying Hydro-Clone is its ability to act as a virtual sensor, providing a reliable reference based on physical modeling when actual measurements become unavailable or corrupted. Figure 6 shows an example in which the measured surge tank water level exhibits spurious values due to a malfunction in the data acquisition card, while the Hydro-Clone simulation continues to produce stable and physically consistent results. In such cases, the digital twin serves as a baseline reference for how the system should behave under the given operating conditions. This allows operators to confidently identify sensor faults and maintain operational awareness using the simulated output, effectively bridging the gap until the faulty sensor is repaired or replaced.

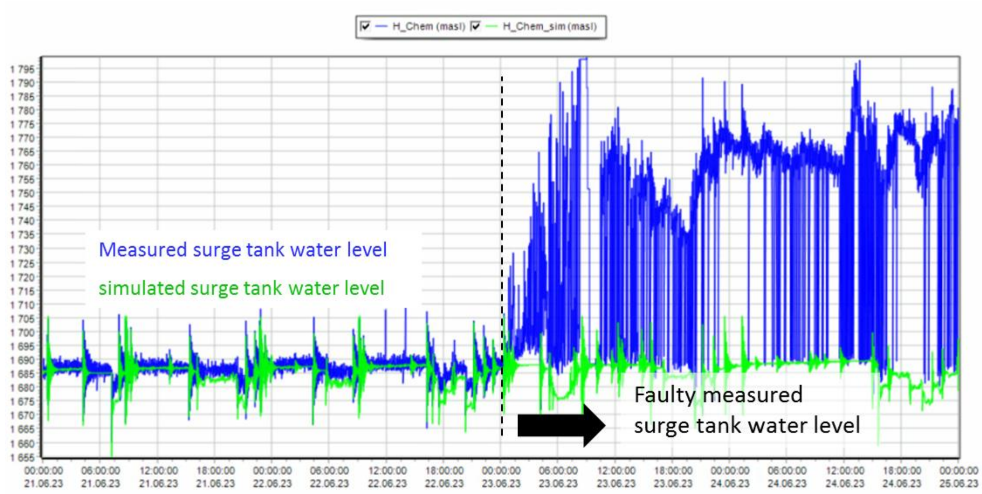

Figure 6. Measured (blue) and simulated (green) surge tank water levels during a sensor malfunction period, where the measurements produced erroneous data..

4.3 Pelton "Falaise effect" detection

The *Falaise effect* refers to a sudden drop in efficiency and active power in a Pelton turbine when the water jets lose sufficient speed to properly evacuate the buckets, typically caused by a rapid pressure drop at the turbine inlet. This phenomenon was first identified at Grand'Maison during emergency shutdowns (ESD) of pump-turbines operating in pump mode under low head conditions. In the scenario of HSC operation with a Pelton unit connected to the same pressure shaft, an ESD of the pump-turbines can induce an abrupt pressure drop that results in a nearly instantaneous power loss in the Pelton unit.

This effect was confirmed by site measurements prior to the deployment of Hydro-Clone and was later reproduced using SIMSEN simulations. As illustrated in Figure 5, the model accurately predicted the onset of the power loss when the surge tank water level, and thus the net head at the unit, fell below a critical threshold. However, while the simulation predicted a rapid recovery, the measured power remained low for several minutes, due to persistently low jet velocity and incomplete bucket evacuation, resulting from 3D phenomena not captured in the 1D model or in the turbine characteristic curves. With Hydro-Clone now operational, the system can detect such discrepancies in real time by comparing measured and simulated power output, allowing for immediate identification of the *Falaise effect*, which enables EDF to deploy appropriate countermeasures to recover turbine power.

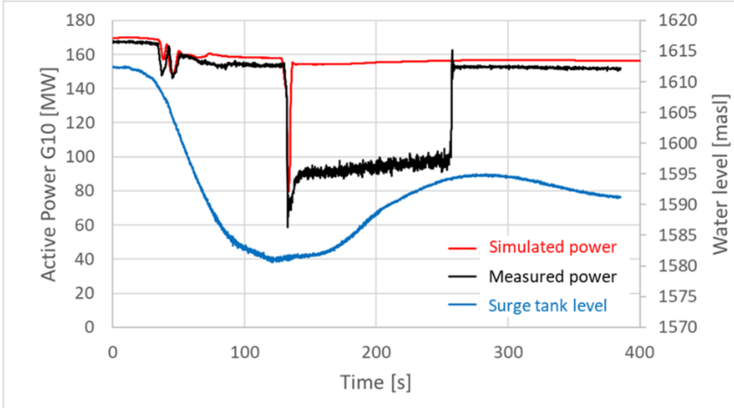

Figure 7. Illustration of the Falaise effect with simulated and measured active power and the corresponding water level in the surge tank.

4.4 Recommissioning of the G1 Pump-Turbine

The Hydro-Clone digital twin was particularly useful in validating the dynamic behavior of the G1 pump-turbine during recommissioning tests following its complete overhaul in December 2024. These tests included transient scenarios such as emergency shutdowns (ESD) in both turbine and pump modes. The digital twin confirmed that key parameters, including spherical valve closure times, unit inertia, and pressure surge amplitudes, remained consistent with pre-rehabilitation values. Moreover, the ability of the model to accurately reproduce transient phenomena, including water hammer effects and mass oscillations, enabled reliable predictions of discharge and pressure during specific overspeed tests, prior to performing the site measurements.

Real-time comparisons between simulated and measured data further verified that the G1 unit's efficiency and hydraulic performance were maintained post-rehabilitation. Figure 8 presents the measured and simulated penstock pressure during an emergency shutdown in pump mode. Pressure envelope analysis confirmed compliance with design limits across the waterway. These capabilities streamlined the recommissioning process, reduced downtime, and gave operators confidence in the unit's restored operational integrity.

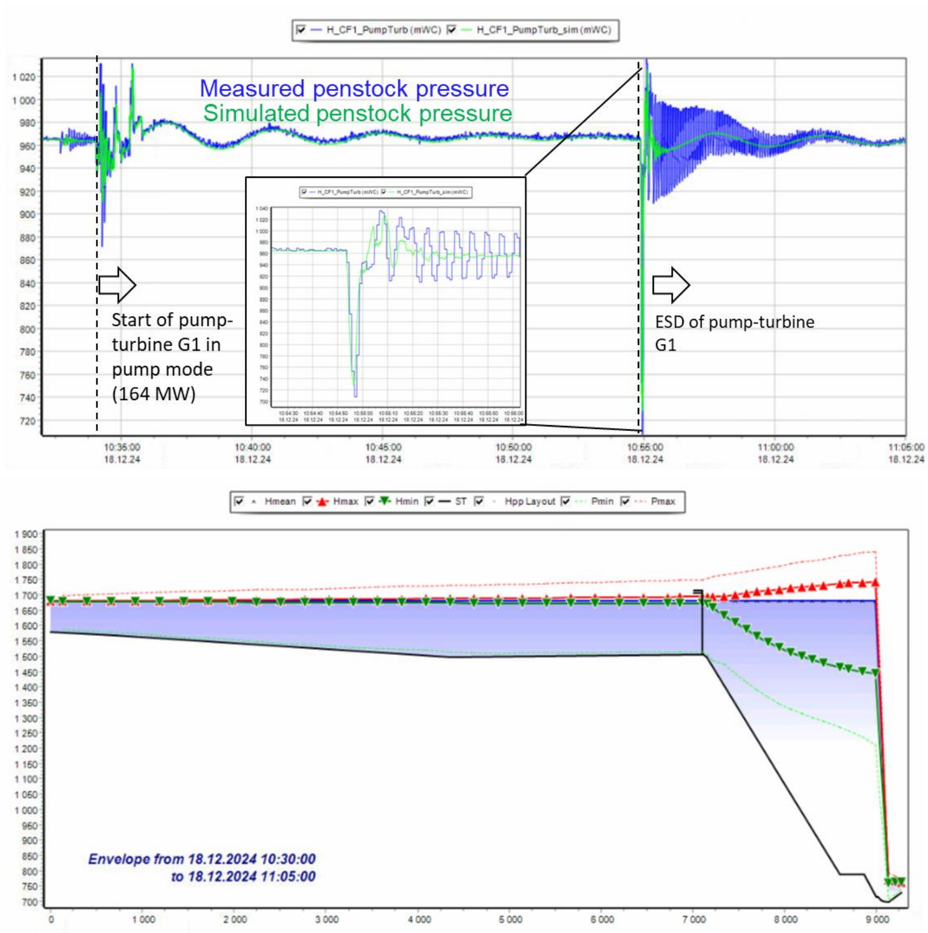

Figure 8. Top: Measured (blue) and simulated (green) penstock pressure during the start-up and ESD of unit G1 in pump mode. Bottom: Resulting maximum (red) and minimum (green) pressure envelope along the waterway, with the alarm threshold indicated by the dashed line.

4.5 Inertial response of units during Iberian Peninsula blackout

On Monday 28 April 2025 a major power blackout occurred across the Iberian Peninsula, triggered by a cascading grid failure. This event provided a rare opportunity to observe the inertial response of Grand'Maison's units under extreme frequency deviations (reaching 600 mHz/s). During the event, the plant operated in hydraulic short-circuit (HSC) mode, with three pump-turbines (G4, G6, G7) in pumping mode and two Pelton turbines (G11, G12) generating. Thanks to Hydro-Clone's 10 Hz data acquisition, the rapid response of the synchronous machines to the frequency disturbance was captured, revealing an inertial power contribution of approximately 20 MW per unit.

Notably, the measurements confirmed that pump units delivered inertial support comparable to turbines, as illustrated in Figure 10. While Hydro-Clone hydraulic simulation (which excludes electrical modeling) did not replicate this power injection, the discrepancy between measured and simulated outputs clearly highlighted the phenomenon. These results empirically demonstrate that HSC operation not only enhances flexibility but also increase inertial response capabilities of the plant, confirming earlier expectations reported in [8], and offering critical insights for future grid resilience strategies.

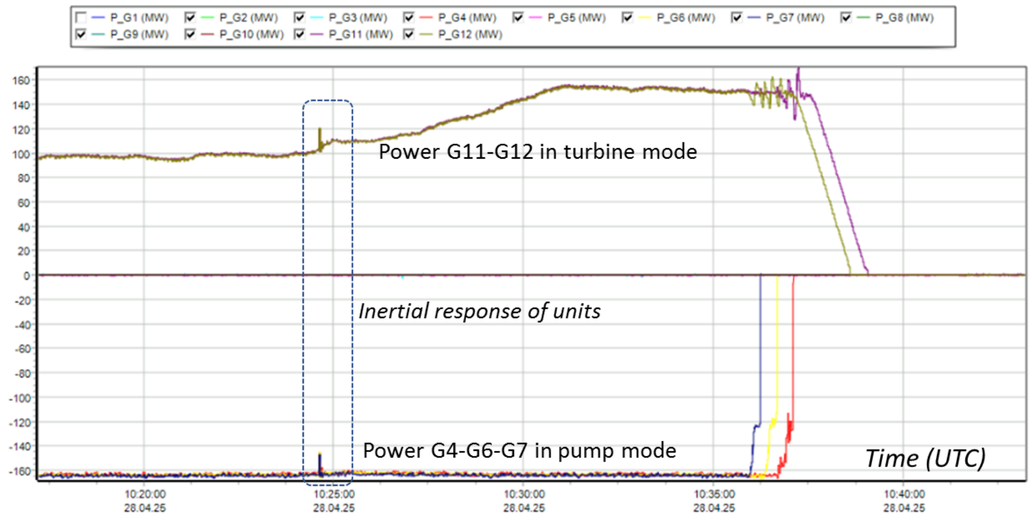

Figure 9. Recorded inertial response of the Grand'Maison units during the 28.04.2025 Iberian Peninsula blackout.

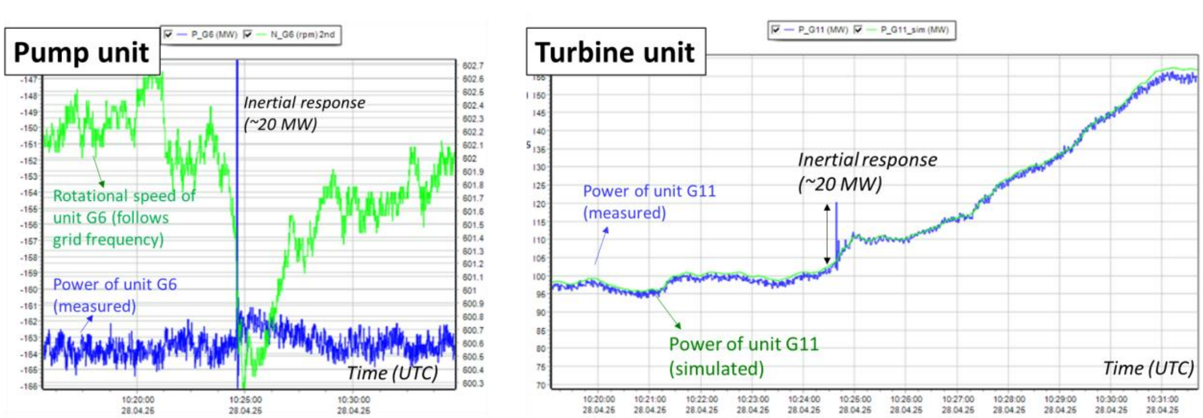

Figure 10. Measured 20 MW inertial response from Grand'Maison units G6 (operating in pump mode) and G11 (Pelton turbine in turbine mode) during the Iberian blackout on April 28, 2025. The simulated power does not capture this response, as the hydraulic model does not account for electromechanical dynamics

5. Conclusions

The deployment of the Hydro-Clone digital twin at Grand'Maison PSPP has demonstrated the benefits of real-time simulation in monitoring and supporting complex hydropower operations. By combining a validated SIMSEN model incorporating actual plant data, Hydro-Clone can accurately capture transient hydraulic behavior and provide valuable insights during critical events such as hydraulic short-circuit operation, sensor failure and unit recommissioning. It provides a virtual reference for unmeasured variables, improves operational diagnostics and facilitates the safe integration of new operating modes, such as on-the-fly recoveries. In addition to real-time monitoring, the alarms and anomalies detected by Hydro-Clone can serve as a basis for generating automatic annual reports, helping to identify hidden or recurring phenomena that might otherwise go unnoticed by conventional monitoring. These results emphasize the increasing benefits of digital twins in enhancing the reliability, flexibility, and resilience of modern pumped-storage plants.

Acknowledgements

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