Hydraulic Transient Survey at Cleuson-Dixence with Real-Time Hydro-Clone Monitoring System

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Introduction

Hydropower plants (HPP) play an important role for electrical power network stability due to their operational flexibility and their ability to provide ancillary services such as primary, secondary and tertiary control services. These services lead to frequent start and stop sequences, as well as continuous power variations inducing hydraulic transient phenomena in the waterways. Moreover, control system modernisation enables faster response of the hydropower units, which are more and more operated with remote control. As a consequence, existing hydropower plants are subject to new operating conditions and sequences which were not foreseen during the conception. This significant increase of load variations enhances fatigue problems.

To address the issue of sound transient survey, an application of Real-Time Simulation Monitoring (RTSM), defined as “hydro-cloning”, has been developed by Power Vision Engineering. Since 2014, this system has been successfully implemented in 6 hydropower plants in Switzerland, including the Cleuson-Dixence HPP, in the Canton of Wallis, Switzerland, which features the world most powerful Pelton turbines as well as the highest head used to produce hydro-electric energy.

This article introduces the Hydro-Clone system, an innovative Real-Time Simulation Monitoring (RTSM), developed by Power Vision Engineering Sàrl for waterway hydraulic transient survey, and its successful implementation at the 1269 MW Cleuson-Dixence power plant, owned by Grand Dixence SA and Alpiq Suisse SA, operated by HYDRO Exploitation SA, in the Canton of Wallis (Switzerland). This power plant comprises 16 km long headrace tunnel, a surge tank, a 4.3 km long pressure shaft feeding 3 Pelton turbines of 423 MW with a total discharge of 75 m3/s and operated under the world record maximum gross head of 1883 mWC, [1]. The pressure shaft was subject to a rupture in December 2000, and was recommissioned in 2009 after penstock relining in the original pressure shaft and by-pass of the accident zone [2], [3], and the power plant was put back into normal operation in January 2010, [4]. Therefore, due to ultra-high head and large capacity, the hydraulic transients and related waterway condition is of very high importance at Cleuson-Dixence. Therefore, the Hydro-Clone system, comprising a simulation model of the power plant, a Real-Time management system linking the actual power plant with the clone or digital power plant, and a monitoring system delivering transient phenomena based alarms was recently deployed. By sound calibration of the simulation model and by real-time use of in-situ measurements, the transient behaviour of the power plant is instantaneously replicated, generating in this way a full and reliable “digital clone” of the real power plant. The clone enables to monitor the hydraulic transient along the entire waterways from the intake to the Pelton turbine nozzles.

This article also presents the different type of alarms addressing detection of extreme pressure along the headrace and pressure shaft but also enabling to detect possible anomalies in case of significant divergences between simulation and measurements. Finally, the paper presents analysis of peculiar pressure transients events induced by normal operation with primary and secondary control service and discuss possible means to reduce their amplitudes and impacts on the pressure shaft structure lifetime.

1. Presentation of Cleuson-Dixence power plant

The Cleuson-Dixence power plant comprises an upper reservoir constituted by the Grande Dixence dam, see Figure 1 a), with a maximum water level of 2364 masl, a head race tunnel of about 16 km long, a surge tank with upper and lower expansion chambers, a pressure shaft of about 4260 meters long and a mean diameter of 2.85 m, the Bieudron powerhouse with 3x423MW Pelton units with vertical axis and 5 injectors at elevation 481masl, see Figure 1 b), and 3 spherical valves of 1.4 m diameter, see Figure 2 and Figure 3. Table 1 provides the main characteristics of this power plant featuring a maximum gross head of 1883 mWC with a nominal discharge of 75 m^3/s.

a) b)

Figure 1 a) Grande Dixence Dam: the tallest gravity dam in the world. b) Bieudron Power house of 3x423 MW.

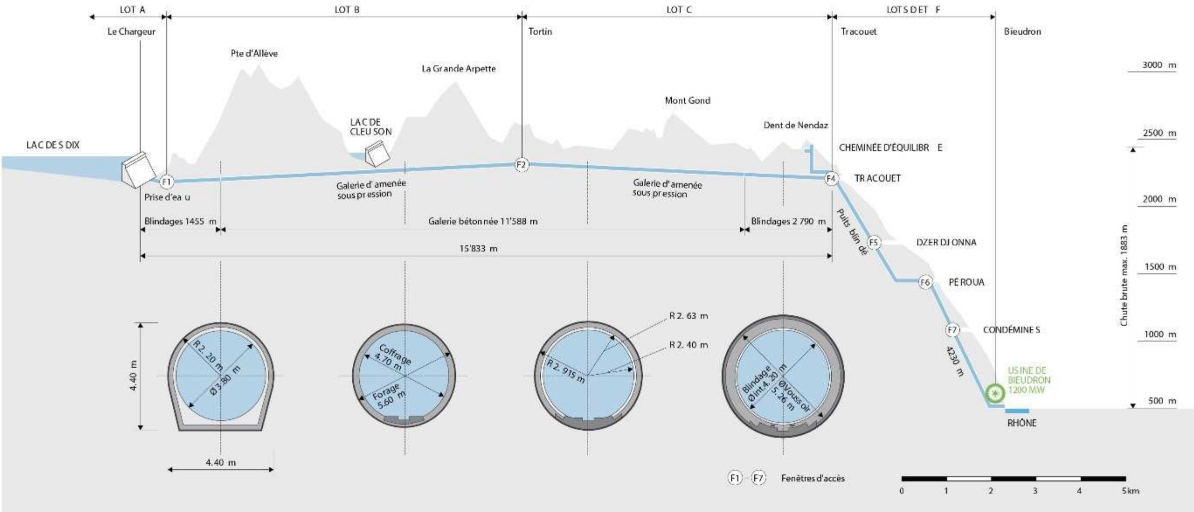


Figure 2 Hydraulic layout of Cleuson-Dixence power plant

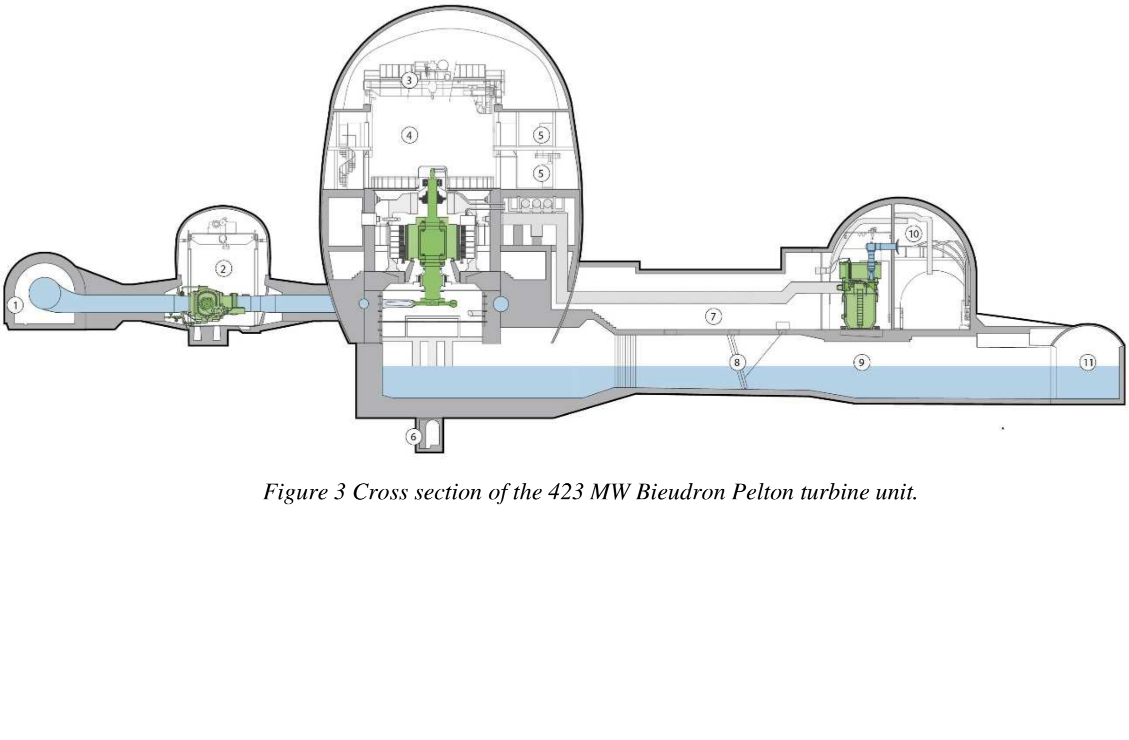


Figure 3 Cross section of the 423 MW Bieudron Pelton turbine unit.

Table 1 Cleuson-Dixence plant main characteristics.

Description	Value
Installed capacity	3x423 MW
Maximum gross head	1883mWC
Total nominal discharge	75 m3/s
Nominal rotational speed	428.6 rpm
Number of injectors per unit	5
Pelton runner diameter	3.993 m
Rotating axis orientation	Vertical

2. The Hydro-Clone Real-Time Simulation Monitoring System

2.1. General description

The Hydro-Clone is an innovative Real-Time Simulation Monitoring System (RTSM) comprising a soundly calibrated and validated numerical copy of a HPP able to reproduce in real-time any dynamic behavior of the power plant based on *in-situ* measured boundary conditions, *i.e.* a digital clone. This system, subject to patent see [5], allows to continuously diagnose the health of a HPP by real-time numerical cloning of the major hydraulic and electrical components of the plant, using the SIMSEN software [8], [11] and existing key monitoring points. The Hydro-Clone system comprises the following components:

- A calibrated and validated SIMSEN simulation model of the HPP, operated in Real-Time and using *in-situ* measured boundary conditions. This model may include:
    - the hydraulic circuit, comprising galleries, surge tanks, valves, pressure shaft, turbines;
    - the rotating train, comprising the mechanical inertia and coupling shaft;
    - the electrical system, comprising motor-generator, transformer, circuit breakers, transmission lines.
- A real-time monitoring system performing the following tasks:
    - acquisition of *in-situ* measured quantities;
    - transfer of these boundary conditions to the simulation model;
    - management of the clone real-time simulation of the real HPP;
    - data processing and diagnosis of the power plant health;
    - provide pre-defined appropriate alarms based on both real-time (RTSM) and ahead-of-time (ATSM) analysis;
    - display of relevant on-line information of the health condition of the HPP;
    - communication with tailor-made archival storage system;
- A tailor-made archival storage and related database system enabling:
    - to archive simulated and measured quantities;
    - to display and analyse previous results;
    - to log alarms;
    - to update and enhance the clone functioning.

As illustrated in Figure 4 and Figure 5, the numerical simulation model benefits from measured boundary conditions, such as upper and lower reservoir water levels and guide vanes/injectors openings, to reproduce with high accuracy the dynamic behaviour of the hydraulic installations. Optionally, the electrical systems can also be simulated taking into account the power network voltage and frequency and the motor-generator excitation currents, [6]. The analysis and the comparison of simulated and measured quantities enable to:

- understand at any time the health state and behaviour of all essential components of the system;
- estimate non-measured /non-measurable quantities throughout the whole system;
- switch to numerical values in case of lack/defect in measurements;
- detect hydraulic/electric anomalies in real time by means of a system of automatic alarms;
- perform ahead-of-time projections of the state of the system by automatic prediction simulations based on actual real-time state of the system;
- anticipate any potential near-future damage to be caused by the system to the outside environment, based on its real-time state;
- perform on-line or off-line analysis to evaluate a wide range of potential risks, such as for example components fatigue or buckling of steel lines resulting from past operation.

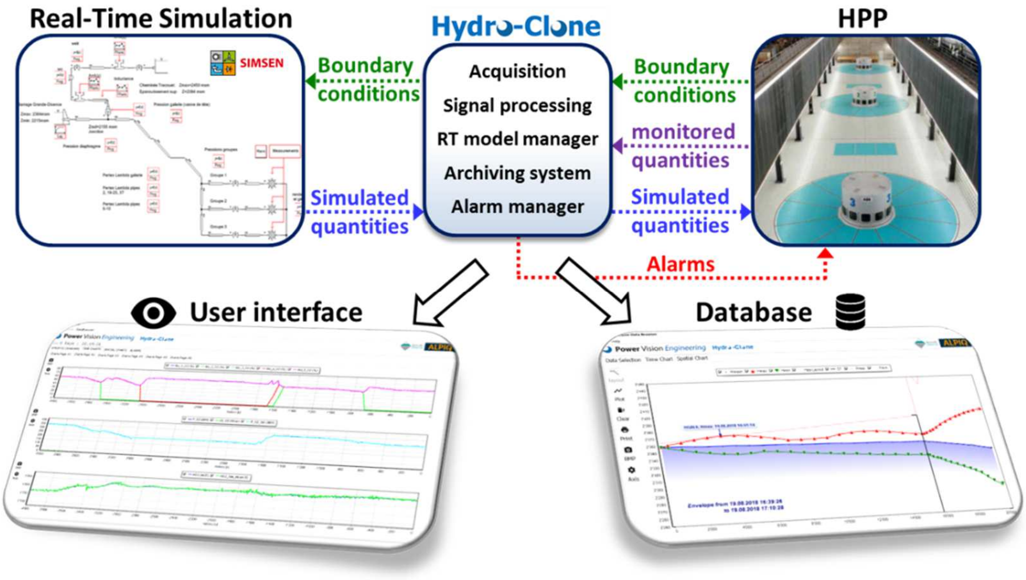


Figure 4 General concept of Hydro-Clone based on Real-Time Simulation of HPP.

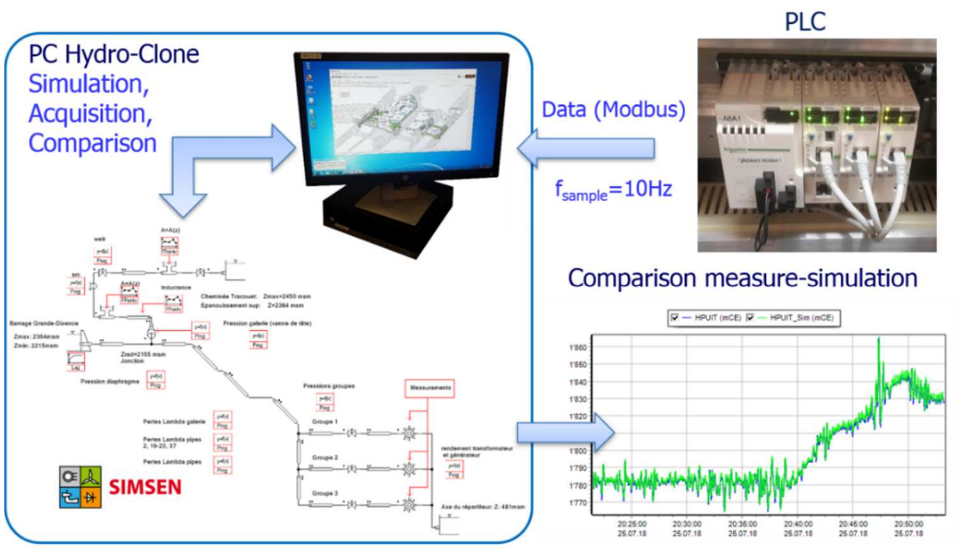


Figure 5 Implementation of the Hydro-Clone system, as used in the Cleuson-Dixence HPP.

2.2. Implementation of Hydro-Clone to Cleuson-Dixence HPP

Figure 7 presents the SIMSEN model of the Cleuson-Dixence HPP, showing the different elements covered by the corresponding Hydro-Clone. The model comprises the upper reservoir, the headrace tunnel, the surge tank with the upper expansion chamber, the pressure shaft, the manifold and the three Pelton turbine units. The turbines are modelled with their characteristics, while active power is calculated according to unit efficiency hill charts and generator efficiencies. The differential surge tank behaviour of the upper expansion chamber, illustrated in Figure 6, has been thoroughly modelled. The SIMSEN model accounts for water hammer, surge tank mass oscillation and Pelton turbine transients phenomena, see [8], [9], [11].

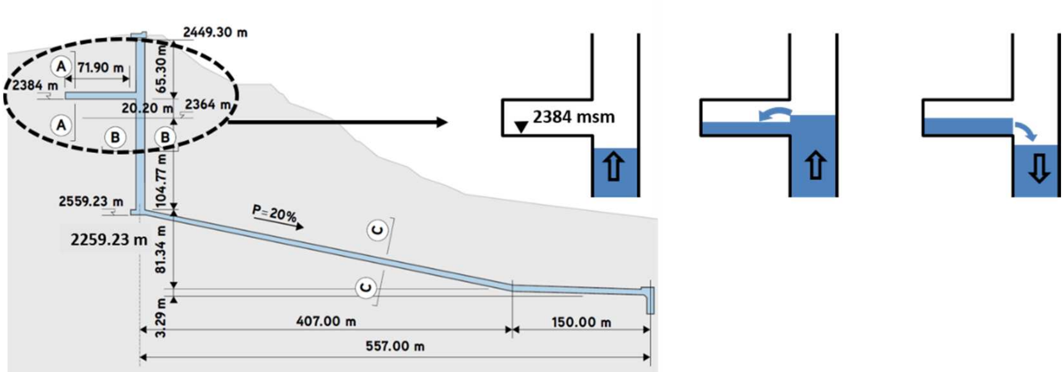


Figure 6 Differential surge tank behavior in the upper expansion chamber.

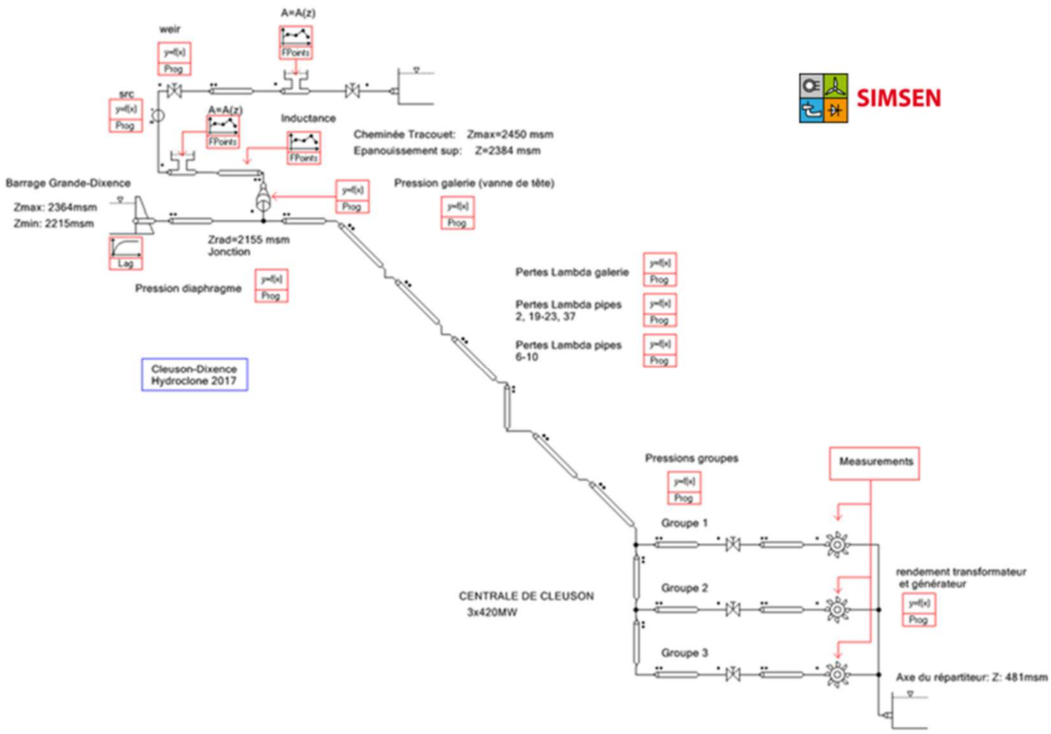


Figure 7 Cleuson-Dixence power plant SIMSEN model.

The quality of the numerical model can be appreciated in Figure 8, which presents the comparison between the simulated and measured pressure in the manifold, as well as the surge tank water level, during an 1200 MW quick shutdown of the installation performed during recommissioning, [4]. A very good agreement is observed with the on-site measurements in terms of maximum amplitudes of pressure and surge tank water levels. It is important to emphasize that these simulations were not obtained in real-time, but performed off-line with the archived time evolution of the injectors positions and upstream water level as boundary conditions for the simulation.

On the other hand, Figure 9 compares the real-time simulation results with on-site measurements of the manifold pressure (a) as well as surge tank water level (b) obtained with the Hydro-Clone system. The simulations have been performed by imposing upstream water level and measured position of the actual Pelton turbine injectors transmitted via MODBUS protocol. The very good agreement obtained for the manifold pressure and surge tank level confirms the appropriate modelling of the powerplant and the ability of the digital clone to instantaneously replicate the pressure transients of the HPP. Therefore, correct prediction of pressure in the whole headrace tunnel and penstock are also expected. It has to be outlined that all measurements have been obtained based on existing measurements made by the SCADA, and that no additional transducers were necessary to perform the real-time simulation and the model validation.

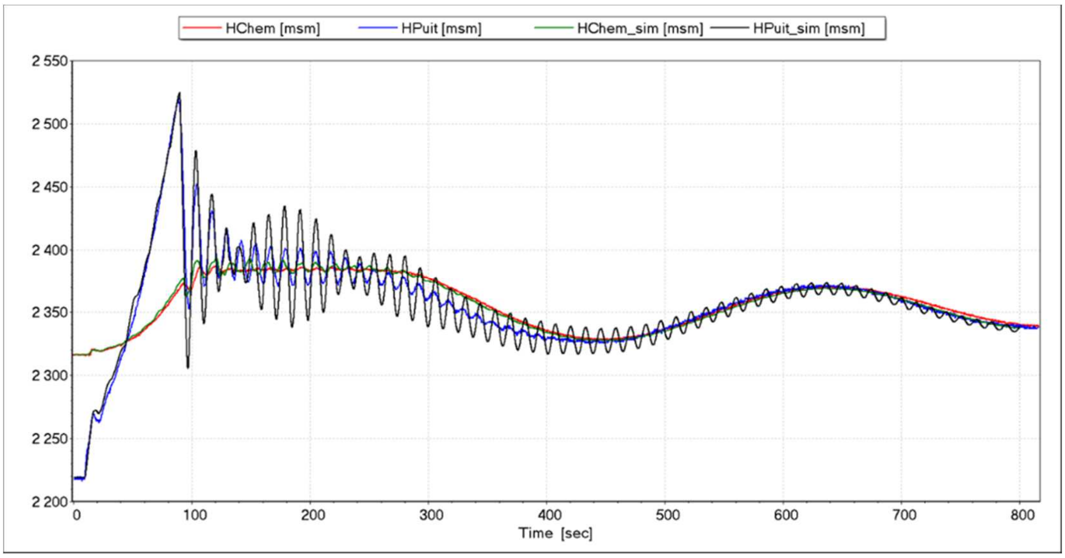
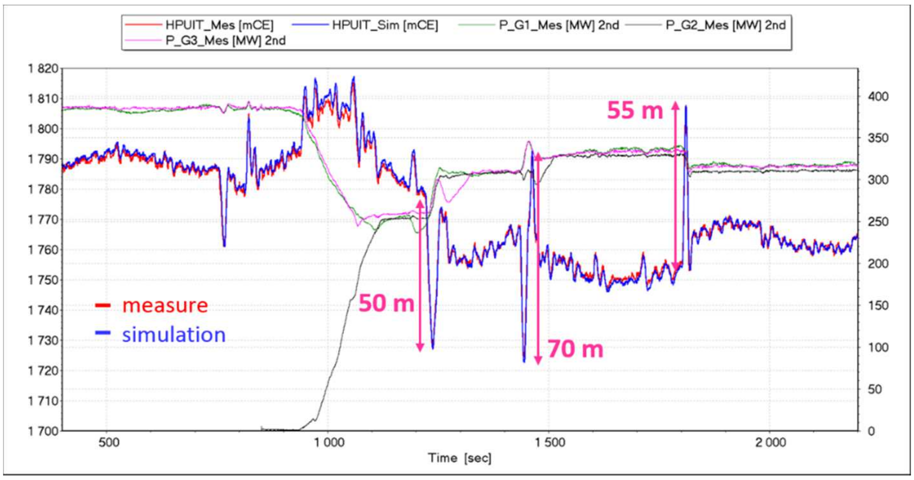


Figure 8 Comparison between offline simulation results and on-site measurements of the pressure in the manifold, as well as the water level in the surge tank, resulting from emergency shutdown on the three units.

a)



b)

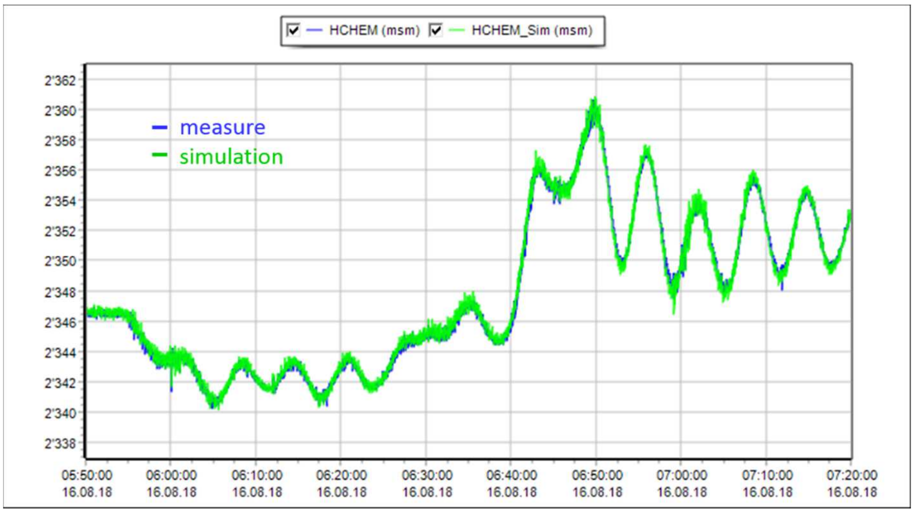


Figure 9 Comparison between real-time simulation results and on-site measurements. a) Pressure in the manifold with the power of each unit. b) Water level in the surge tank.

2.3. The Hydro-Clone interface

The Hydro-Clone user interface allows for a quick and direct comparison of signals coming from the measurement and the simulation results. As represented in Figure 10a and c, this interface comprises some synoptic diagrams of the power plant, on which the instantaneous values of the measured and simulated signals are displayed in boxes, mimicking a traditional SCADA view of installation. In addition, the temporal evolution of each signal can be visualized on some customizable graphics, arranged on different tabs of the interface, as shown in Figure 10b. These graphs display the signals history during the last hour, and the user can easily navigate in them by zooming or changing the axis limits to verify the agreement between the measurements and the simulation. Besides the live visualization functionalities, the Hydro-Clone system offer the possibility to browse and visualize past events, archived in a dedicated database.

The digital clone provides the ability to visualize in real time the evolution of the piezometric head in the headrace tunnel and the penstock, represented in Figure 10c, where the water level is depicted in blue on top the HPP layout, along with the admissible values in the headrace tunnel. The pressure values constituting the piezometric line are a good example of non-measurable quantities obtained from the simulation model in real-time. Moreover, the daily pressure envelopes are accessible via the consultation of the archived events.

Finally, the interface contains the alarms handling features with the alarms acknowledgment functionalities and alarm log consultation. The Hydro-Clone alarms are transferred to the SCADA of the HPP and are treated as a conventional alarm by the already installed control system.

a) b)

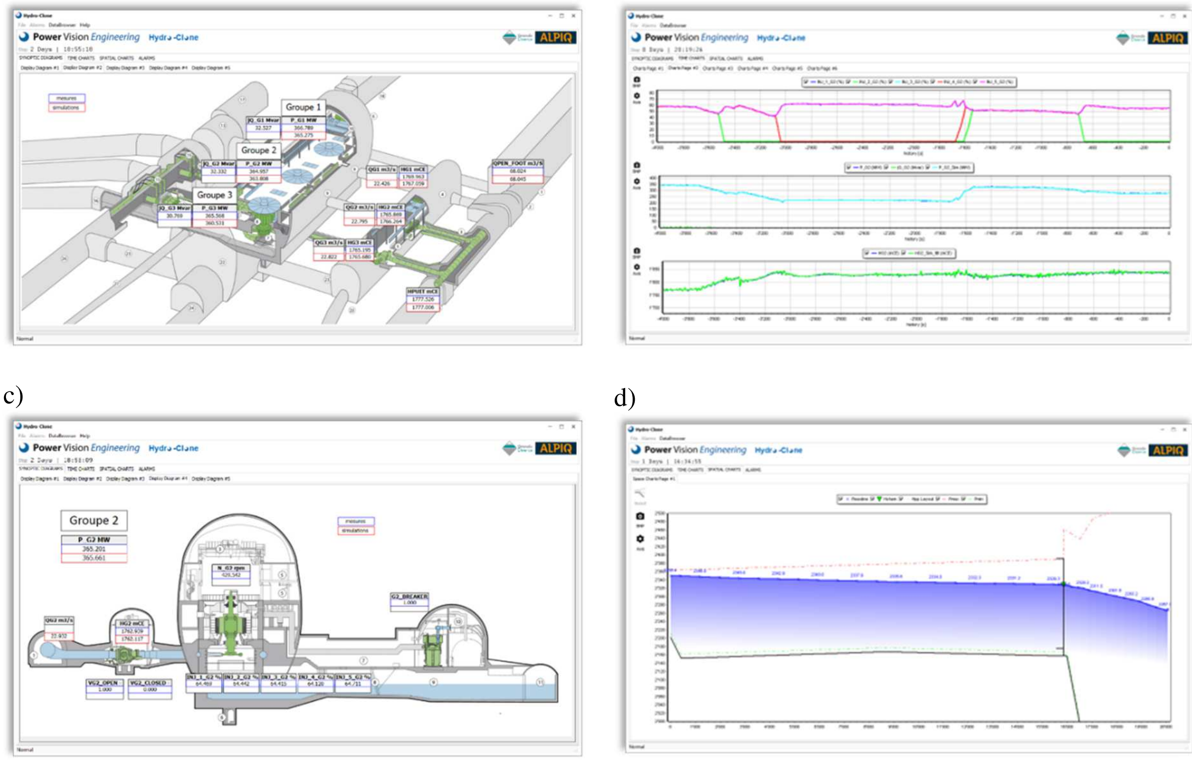


Figure 10 Snapshots of the Hydro-Clone interface. a) and c) synoptic diagrams, b) temporal graphics, d) real time evolution of the piezometric line.

3. The Hydro-Clone Alarms

The objective of Hydro-Clone is to detect and prevent equipment malfunctions or anomalies that may affect the hydraulic transients of a HPP, in order to reduce the risk of a major accident that could jeopardize the integrity of the facilities and people. To this end, the Hydro-Clone monitoring system provides 3 different types of alarms, based on the following criteria and illustrated in Figure 11.

- Type 1: Exceedance of the admissible limit of a measured quantity (*i.e.* classical monitoring);
- Type 2: Exceedance of the admissible limit of a non-measurable quantity obtained from the simulation model in real-time, such as:

- minimum or maximum pressure throughout the penstock or the headrace/tailrace tunnels;
- discharge throughout the system;
- extreme torque in the coupling shaft;
- extreme current or voltage in electrical system;

- Type 3: Divergence between measurements and simulations, to identify possible anomalies such as:
  - unexpected gate or valve closures;
  - unexpected air admission from air-valves;
  - flow obstruction by external body;
  - head loss increase;
  - water column separation;
  - conduit breakdown;
  - surge tank sediment deposit;
  - electrical fault.

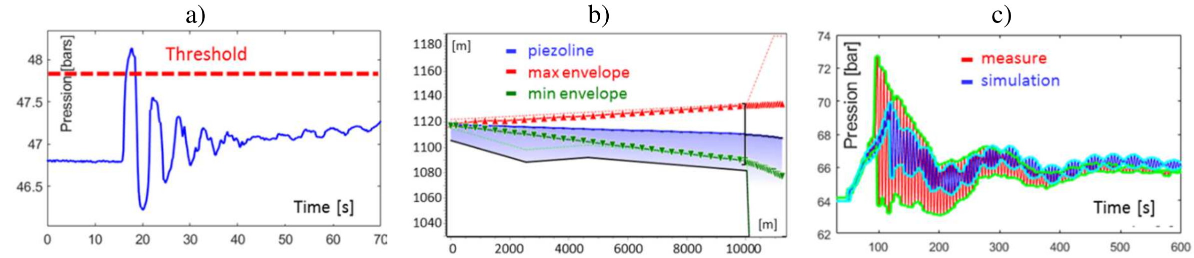


Figure 11 Type of Hydro-Clone alarms: a) type 1: Exceedance of the admissible limit of a measured quantity; b) type 2: Exceedance of the admissible limit of a non-measurable quantity; c) type 3: Divergence between measurements and simulations.

The signal processing in the case of the type 1 and 2 alarms is trivial: an event is triggered as soon as the signal exceeds a threshold value, see Figure 11a and b. However, for the type 3 alarm, a special signal analysis is implemented in the Hydro-Clone system, in order to reliably detect a divergence between measurements and simulations. The procedure can be summarized as follows: first the signals envelopes are calculated in real-time, to filter out the oscillations due to water hammer. Then, two auxiliary signals, representing the mean signal value and peak-to-peak amplitude, are derived from these envelopes. Finally, the agreement between two signal is assessed by computing the mean-squared error (MSE) between each auxiliary signal (mean envelope and amplitude). This procedure allows to assess the similarity between two signals both in terms of average value as well as the general signals shapes.

An example of divergence detection between measurements and simulations is given in Figure 12. Case (a) depicts a pressure transient event measured at Emosson HPP [14], due to unappropriated main inlet valve closing time. Since this event was not taken into account in the simulation, the divergence between the two signals is clearly highlighted by the divergence of signal amplitudes, as evidenced by the high value of the corresponding MSE indicator. On the other hand, case (b) illustrates a drift in the measured pressure signal which occurred at the FMHL HPP [15]. As it can be observed, the MSE between the signal of the mean envelopes clearly detect the signal drift, while the MSE between the signal amplitudes remains low, reflecting the similarity of the general signal shape.

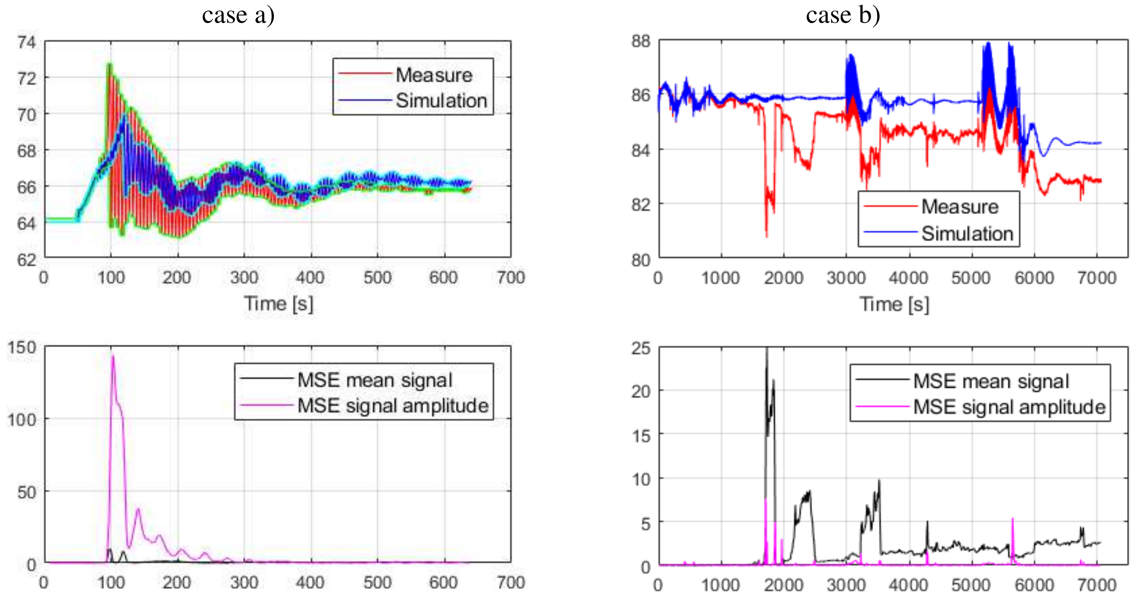


Figure 12 Example of the signal processing for the type 3 alarm. Case a): pressure transient resulting from fast main inlet valve closing measured at Emosson HPP [14], detected by the divergence of the signal amplitudes. Case b): Measured signal drift at the FMHL HPP [15], detected by the MSE between the mean signal values.

4. Results and discussion

At the writing of this article, the Hydro-Clone system has been running continuously in real-time operation for about 8 months. During this period, the reliability of the system has been thoroughly tested and the benefit of real-time monitoring has been revealed through several outcomes regarding the HPP operation, presented hereafter.

4.1. Pressure fluctuations induced by secondary control service

Figure 13 presents a direct comparison of the simulated and measure pressure in the manifold during the starting of a unit, alongside with the position of all the injectors (right axis). As it can be observed, if the measurements and simulation coincide almost perfectly, this sequence presents several important pressure fluctuation occurring in a period of 20 minutes following the start of the second unit. The origin of each of these pressure transient events can be traced back to the programmed injectors movement during the starting of the unit. In particular, it can be seen that the injectors opening sequence, used to accelerate the turbine and synchronize its speed, induces a pressure fluctuation of 45 m amplitude at the penstock bottom. In addition, the injectors combination changes which follow the engagement of the additional unit induce two pressure transients events with amplitudes of 50 m and 70 m, respectively. Finally, this sequence exhibits a 55 m peak-to-peak pressure fluctuation when all the injectors close slightly simultaneously to meet a new power setpoint defined by the secondary control.

Such sequence of events resulting from normal operation with primary and secondary control service occur several times a day and contributes directly to pressure shaft fatigue. It was noticed that significant power setpoint changes were triggered every full hour as a result of the electricity market and transmission system operator, TSO, adjustment through the secondary control. The monitoring established by Hydro-Clone helped to quickly notice these important pressure transients events which have a negative impact on the pressure shaft structure lifetime. Following the identification of these pressure fluctuations, control parameterisation could be undertaken in order to limit pressure amplitudes while still complying with the TSO requirements.

The excellent agreement between simulation and measurements demonstrates the ability of the digital clone to replicate with high fidelity the pressure along the penstock. By coupling this feature with the pressure shaft mechanical characteristics, a new fatigue module is currently under development, and will be incorporated to Hydro-Clone, in order to estimate the remaining lifetime of penstocks according to the accumulated constraints during their past and future operations.

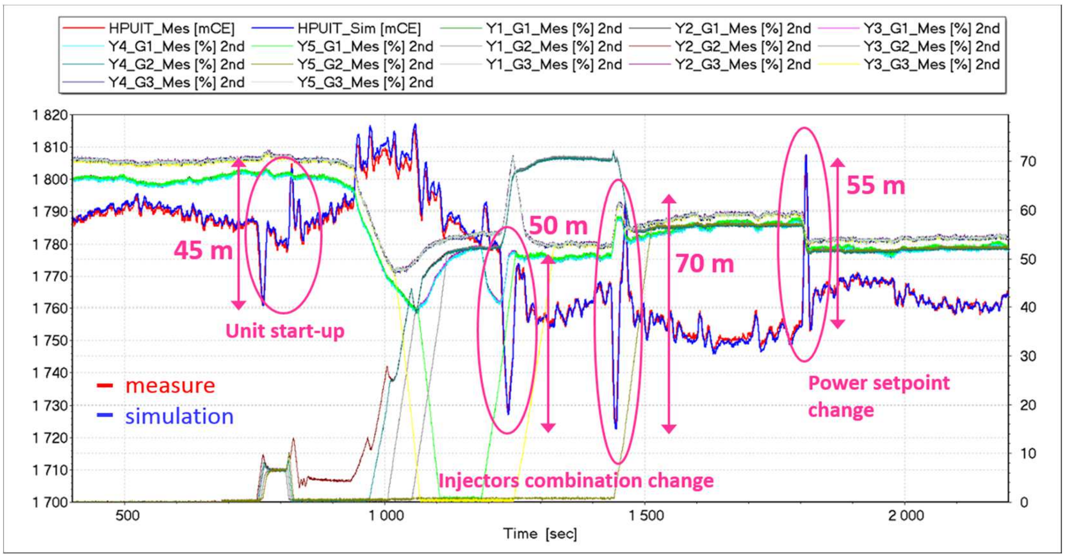


Figure 13 Pressure transient events in the manifold resulting from secondary control services.

4.2. Filter induced pressure amplitude reduction

One of the benefit of the digital clone is that, provided that the model is soundly calibrate, it provides a basis of comparison to assess the quality of the measured signals. Figure 14a depicts a pressure fluctuation measured in the manifold, at the extremity of the distributor, while Figure 14b represents the same event with the group pressure of the first unit, measured at the location of the spherical valve. The measurements and simulations agree well for the manifold pressure, giving a fluctuation amplitude of 55 m. However, in the second case, the pressure sensor indicates an amplitude 20% lower than the simulated one. This divergence is related to the signals conditioning, which are filtered for the group pressures, unlike the manifold pressure. This observation is confirmed by the fact that, if the simulated pressure is filtered with a 2 seconds time constant, the coincidence between measurement and simulation is perfect, yielding a pressure amplitude of 44 m.

This example demonstrates that, due to signal conditioning, the measurement values may underestimate the amplitudes of the pressure fluctuations which occur in the manifold. By providing a neutral basis of comparison between the different pressure sensors, the digital clone quickly brought this situation to light.

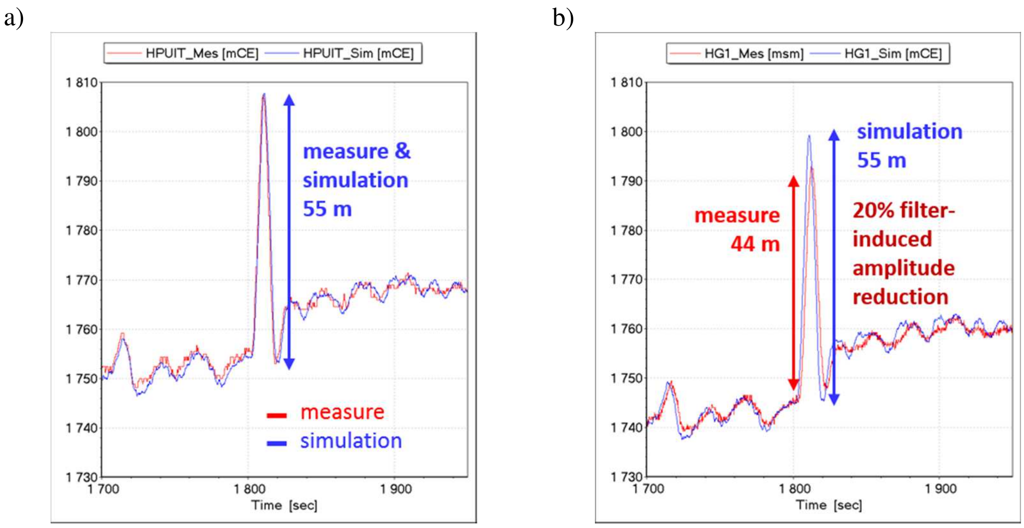


Figure 14 Amplitude reduction of the group pressure induced by the filtering of the measured signals. a) Unfiltered manifold pressure: the measure and simulation are in agreement. b) Filtered group pressure, the measurement is 20% lower than the simulated value.

4.3. Pelton turbine unit differences

As represented in Figure 7, each Pelton turbine is modelled independently in the numerical model. This modelling takes into account the injector discharge characteristics, while active power is calculated according to unit efficiency hill charts and generator efficiencies. From a mathematical point of view, the three units are treated equally in the model, i.e. with the same physical parameters and characteristics. With this in mind, Figure 14 illustrates that, if the simulated and measured power of the unit 3 coincides perfectly, the measured power of the units 1 and 2 is respectively 3% and 1% higher than the simulated one. It should be mentioned that for each of these cases, the simulated penstock discharge is in good agreement with the measured value and that the head losses in the distributor are taken into account in the model.

The root cause of this discrepancy between the three Pelton units is not clearly identified yet. Possible explanation could be linked to some geometric differences between the units (excluding needle and turbine erosion, which are negligible in the Cleuson-Dixence power plant), e.g. deviations in the actual and theoretical values of the injector openings or injector nozzle. It should be mentioned that to allow for a relevant comparison between the measurements and simulation, a correction factor is introduced in the Hydro-Clone system to account for this efficiency discrepancy between the three units and enable detection of possible deviations between measured and simulated values.

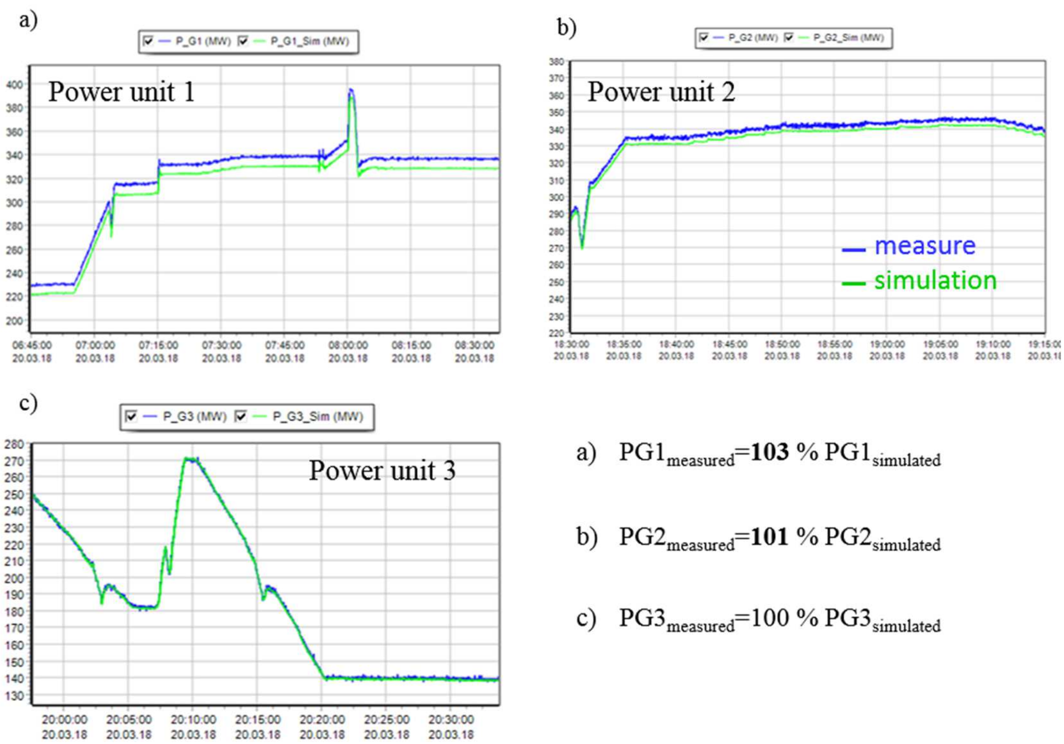


Figure 15 Efficiency discrepancy between the three units. The measured power of unit 1 and 2 is respectively 103% and 101% higher than the simulated value. The measured power of unit 3 corresponds to the simulation.

4.4. Power peak at unit synchronization

In spite of the fact that the numerical model of the HPP used in Hydro-Clone does not include the dynamic behavior of the electrical system, the comparison between measured and simulated power values allows to detect some purely electrical transient events. Figure 16 gives an illustration of one of this event, which occurred during the start of the first unit. As it can be observed, a 50 MW peak in the measured power value was induced at the moment of circuit breaker closure, due to a small synchronization parameters tolerance between the generator and the electrical grid. This type of electrical transient phenomena which are not simulated generate a type 3 alarm, i.e. divergence between measure and simulation, in the Hydro-Clone system. Monitoring theses peak amplitudes can help identify faulty unit synchronizations, which could cause unnecessary shaft solicitations.

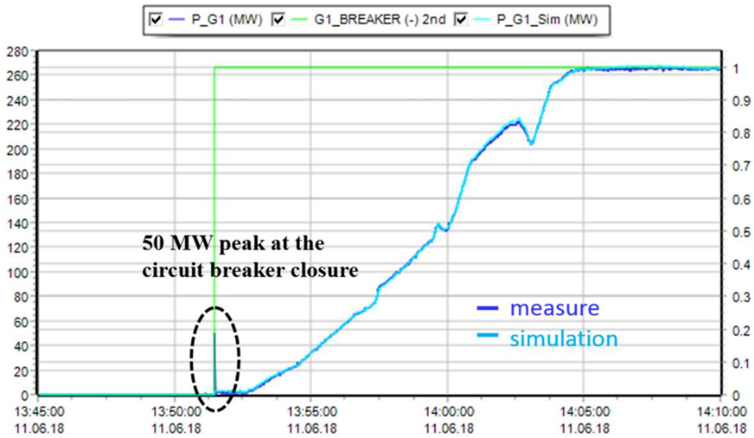


Figure 16 Peak of 50MW in the measured power following the unit synchronization with the grid network

4.5. Surge tank air/water flow

The surge tank of the Cleuson-Dixence HPP comprises a lower expansion chamber, made of an inclined shaft with a 20% slope, followed by a 124 m vertical shaft and a horizontal upper expansion chamber at 2384 masl, see Figure 17a. During the 8 month of the Hydro-Clone operation, the HPP has been operated at different levels of water in the lake, i.e. the reservoir level started low at the spring beginning and has increased continuously due to the natural water supply to reach a maximum in early fall. As a consequence, during normal HPP operation the water level oscillations in the surge tank occur either in the inclined shaft or in the vertical shaft. In both of these cases, the agreement between the simulation and measurement is excellent as illustrated in Figure 17b and d. However, when the water level in the surge tank oscillates across the transition between the inclined and vertical shaft, a clear divergence between the measurements and simulation is observed, see Figure 17c.

The origin of this discrepancy is not known with certitude, but it is strongly suspected that a two phase flow, i.e. air bubbles generation and entrainment, is being generated in this area. Indeed, the shorter oscillation period of the measured water level, as well as the general shape of the signal, are similar to what would be expected in the presence of air bubbles in the water column. Moreover, the volume occupied by the bubbles pushes the surrounding water, yielding a higher water level in the surge tank, which corresponds to Figure 17c, with a measured water level higher than the simulated one. If no air entrainment is expected, possible local defects on the steel lining may occur as a result of the local two phase flow transient, therefore particular attention will be paid at this specific location during the next surge tank inspection.

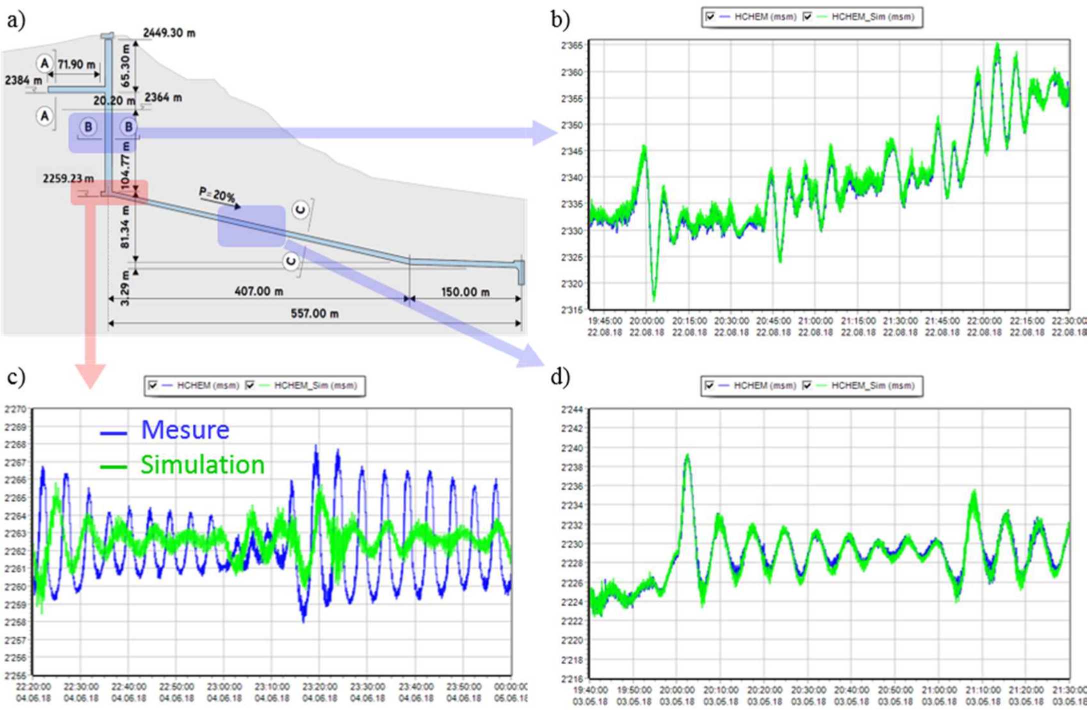


Figure 17 Singular behavior of the water level in the surge tank at the transition between the inclined and vertical shaft, where the simulation and measurement diverge (c). Above (b) and below (d) this section, the correspondence between the measurement and simulation is excellent.

4.6. Headrace tunnel solicitation

During the 8 months of Hydro-Clone real-time monitoring operation, the Cleuson-Dixence power plant was operated at different lake levels, allowing to sweep across a wide range of operation modes of the installation. Figure 18 illustrates a typical transient event which triggered an alarm of type 2, i.e. exceedance of the admissible limit of a non-measurable quantity. In this case, the start of one of the unit generated an important pressure fluctuation in the manifold, depicted by the blue line in Figure 18a. This pressure transient propagated through the hydraulic circuit where the interactions between the penstock and headrace tunnel have excited the headrace tunnel eigenmodes. The resulting pressure envelope in the headrace tunnel is presented in Figure 18b, in which the red and green lines indicate respectively the maximum and minimum pressure levels encountered in the tunnel. The presence of two anti-nodes, with an amplitude of 26 and 35 m, can clearly be observed, indicating that the tunnel 2nd eigenmode is prevailing in this case. These kind of observations allow to identify the areas of the headrace tunnel that are most heavily solicited by pressure transient events.

It should be pointed out that the maximum admissible threshold for the headrace tunnel pressure, depicted by the red dash line in Figure 18b, is arbitrary defined as a straight line between the maximum lake level and the maximum dynamic pressure supported by the surge tank. Although this limit is probably too conservative, it allowed to identify several pressure transient events which excited the gallery 2nd eigenmode.

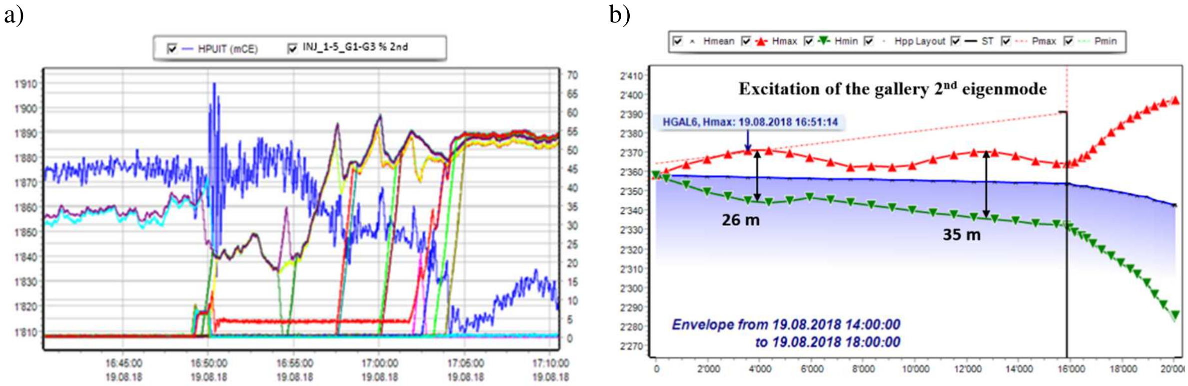


Figure 18 a) Pressure transient event (blue line) in the manifold during a group start-up at high lake level. b) Simulated pressure envelope in the gallery during the same event. The excitation of the gallery 2nd eigen mode is clearly highlighted.

5. Conclusions

The Hydro-Clone system, an innovative real-time simulation monitoring has been successfully implemented at the 1269 MW Cleuson-Dixence power plant, where hydraulic transient are of particular importance due to ultra-high head and long waterways. The main objective of the Hydro-Clone system is to detect and prevent equipment malfunctions or anomalies before the occurrence of accidents or damages, which could jeopardize the integrity of the facilities and people.

After 8 months of successful continuous operation, the benefit of real-time monitoring has been revealed through several outcomes regarding the HPP operation. In particular, the identification of interesting transient phenomena related to secondary control services, led to the control parameters optimization in order to reduce the penstock solicitation, while fulfilling TSO requirements. In addition, the real-time monitoring introduced by Hydro-Clone allowed to identify a possible two phase flow in some location of the surge tank as well as some significant pressure fluctuations in the headrace tunnel resulting from interaction with the penstock water hammer.

The digital clone is applicable to all types of hydraulic machines (Pelton, Francis, Kaplan, pump-turbines), and is based solely on existing measurements, i.e. no additional transducers are required. Since 2014, this system has been successfully implemented in 6 hydropower plants in Switzerland, demonstrating the reliability and maturity of the real-time simulation monitoring concept. For all these reasons, The Hydro-Clone system constitutes indubitably an asset for the power plant safety.

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