# Hydro-Clone: Innovative Real-Time Simulation Monitoring System for Hydropower Plant Transient Survey

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**Abstract**

This article first of all presents an innovative application of Real-Time Simulation Monitoring (RTSM), defined hereafter as "hydro-cloning", developed by Power Vision Engineering. Second, a successful implementation of hydro-cloning is presented for the 170 MW La Bâtiaz hydroelectric power plant, HPP, owned and operated by Electricité d'Emosson SA, in the Canton of Wallis, Switzerland.

The "Hydro-Clone" comprises a simulation model of the power plant, a Real-Time management system linking the actual power plant with the clone or virtual power plant, a monitoring system with transient phenomena based alarms and finally a data base system with remote access. By sound calibration of the simulation model and by real-time use of in-situ measurements, the transient behaviour of the HPP is instantaneously replicated, generating in this way a representative numerical copy of the real power plant, called "the clone".

Long-term tests performed at La Bâtiaz HPP since 2014 confirm the reliability of Real-Time transient computations of complex waterways, including for example transient pressures, discharges, active power of the different units and surge tank water level oscillations. Cloning of a HPP allows detecting unwanted phenomena such as penstock or gallery overpressures, head loss increases, efficiency degradation, surge tank limits, start-up and shut-down issues, unexpected cavitation and possible water column separations, air intake or unwanted valve closures. Furthermore, the clone is able to minimise the risk of potential harming behaviour of the HPP in the near-future by generating so called ahead-of-time simulation monitoring (ATSM) alarms, based on a series of instantaneous simulations of any potential near-future behaviour of the HPP. As such, by combining RTSM and ATSM in real-time, it is believed that the Hydro-Clone reveals to be a valuable numerical asset for any HPP owner to improve power plant safety.

## 1. Introduction

Hydropower plants 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 generate 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. Installed capacity of hydropower plant is also frequently increased during rehabilitation, resulting in an increased discharge in the adduction system. As a consequence, most existing hydropower plants are subject to new operating conditions and sequences which were not foreseen during their conception. Also, the significant increase of load variations and solicitation levels enhances fatigue of aging components. Thus, the exhaustive prediction of transient behaviour of hydropower plants becomes more difficult due to the variety of possible scenarios and unexpected events or sequences, which cannot be excluded.

To address the issue of sound transient survey, an innovative 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 at the 170 MW La Bâtiaz hydroelectric power plant, HPP, part of the 380 MW Electricité d'Emosson SA hydroelectric scheme, in the Canton of Wallis, Switzerland.

The "Hydro-Clone" comprises a simulation model of the power plant, a Real-Time management system linking the actual power plant with the clone or virtual power plant, a monitoring system with transient phenomena based alarms and finally a data base system with remote access. 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 representative numerical copy of the real power plant, called “the clone”.

The simulation model of the La Bâtiaz power plant includes the upper reservoir, the 10’000 m long gallery, the surge tank, the 1’200 m long penstock, the repartitor and the two 85 MW vertical axis Pelton turbines with 5 injectors each. This simulation model, based on the SIMSEN software, accounts for water hammer phenomena in the gallery and in the penstock, for surge tank mass oscillations and for any Pelton turbines transient behaviour. Long term in-situ testing showed the ability of the Hydro-Clone to precisely replicate in real-Time the transient pressures measured at the top and the bottom of the penstock as well as the active power of the units. As such, these tests confirm the reliability of Real-Time transient computations of complex waterways, including for example transient pressures, discharges, active power of the different units and surge tank water level oscillations. Long-term cloning of the power plant enables to detect unwanted phenomena such as penstock or gallery overpressures, head loss increases, efficiency degradation, surge tank limits, start-up and shut-down issues, unexpected cavitation and possible water column separations, air intake or unwanted valve closures.

## 2. The Hydro-Clone

### 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 behaviour of the power plant based on *in-situ* measured boundary conditions, *i.e.* a numerical clone. This system, subject to patent see [1], 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 [4], [7] and existing key monitoring points. As illustrated in Figure 1, the Hydro-Clone 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 includes:
  - 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 contingence alarms;
  - to update and enhance the clone functioning.

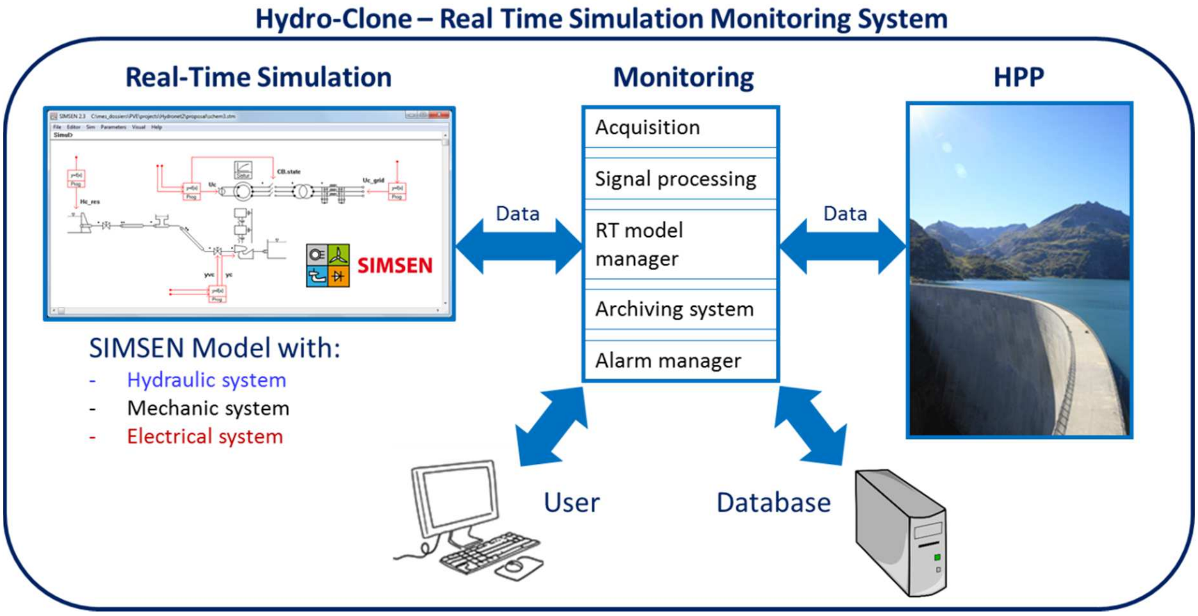


**Figure 1** General concept of Hydro-Clone based on Real-Time Simulation of HPP.

### 2.2. Purpose of Hydro-Clone

As illustrated in Figure 2, the numerical simulation model benefits from measured boundary conditions, such as upper and lower reservoir water levels, guide vanes/injectors openings, power network voltage and frequency and motor-generator excitation currents, to reproduce with high accuracy the dynamic behaviour of both hydraulic and electrical installations. 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.

To this end, as depicted in Figure 2, the Hydro-Clone provides 4 different types of alarms, based on the following criteria:

- 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;
- Exceedance of the admissible limit of a measured quantity (*i.e.* classical monitoring);
- 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;
- Ahead-of-time projections of the state of the system (what-if), to identify possible risks related to pre-defined scenarios such as emergency shutdown, unit loading, or unexpected valve closure.

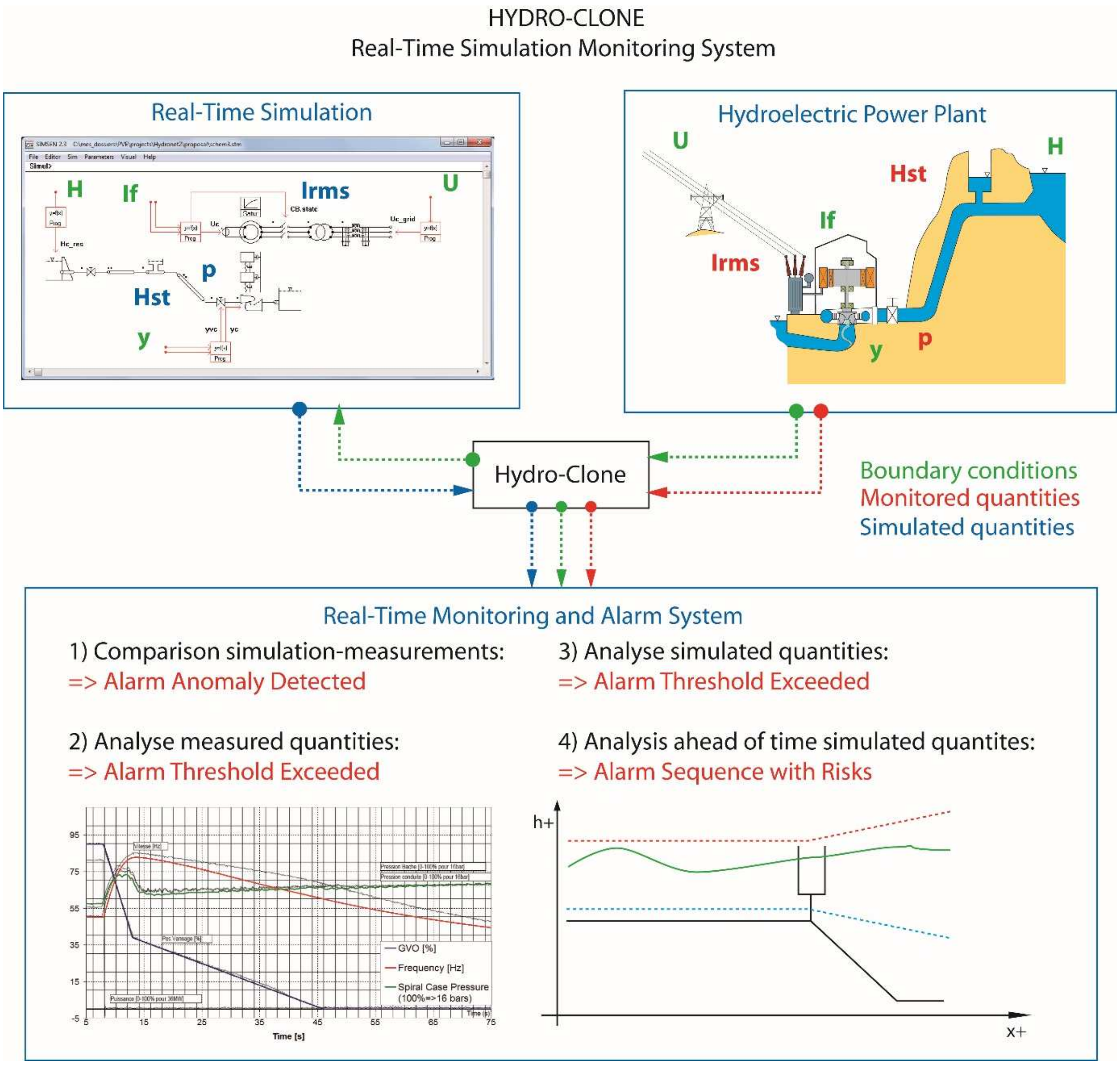


**Figure 2** Data exchange of Hydro-Clone between the Real-Time Simulation Model and the acquisition system, including related alarms.

## 3. Case study of La Bâtiaz HPP

The first Hydro-Clone tests have been performed in collaboration with the company Electricité d'Emosson SA since 2014 at the La Bâtiaz 170 MW HPP located in the Canton of Wallis, Switzerland, see Figure 3 and Figure 4.

Electricité d'Emosson SA is jointly owned by ALPIQ and EDF and collects water from the Mont Blanc Massif, which is channelled into the Emosson Reservoir with a maximum water level of 1930 m a.s.l.. Founded in 1954, the company decided to begin the construction work of the Emosson Dam in April 1967, which became operational on July 1st, 1975. This was made possible by the flooding of the Barberine Dam, previously agreed upon by its owners, the Swiss Federal Railways (CFF); it is now submerged under 42 m of water. The water coming from the high valleys of the river Arve and Eau Noire in France, and, on the other hand, from Val Ferret and Trient Valley in Switzerland, is drained by three headrace tunnels.

Through the South and West collectors located on the French side, the water is routed to the artificial lake by gravity. The volumes from the Swiss side arrive through the Eastern supply line; after passing through the compensation basin of the Esserts, the water may be pumped by the Vallorcine power station to Emosson or/and may be turbined to Châtelard reservoir, depending on natural inflows and electricity management.

With a mean gross head of 1400 m, the two stations of the scheme,i.e. Châtelard-Vallorcine (France, 210 MW) and La Bâtiaz (Martigny, 170 MW), annually generate 850 GWh of energy. The secondary head at les Esserts-Vallorcine is able to directly turbine the volumes arriving through the Eastern supply line when the water is not pumped to Emosson; it is then routed to the lower head of Vallorcine-La Bâtiaz. The water flows back to the Rhone river near Martigny. It has to be mentioned that Electricité d'Emosson SA contributes to both primary and secondary control.

The following subchapters present the SIMSEN modelling of the HPP and its related validation, while the next chapter presents analysis of long term simulations of normal operation of the HPP.

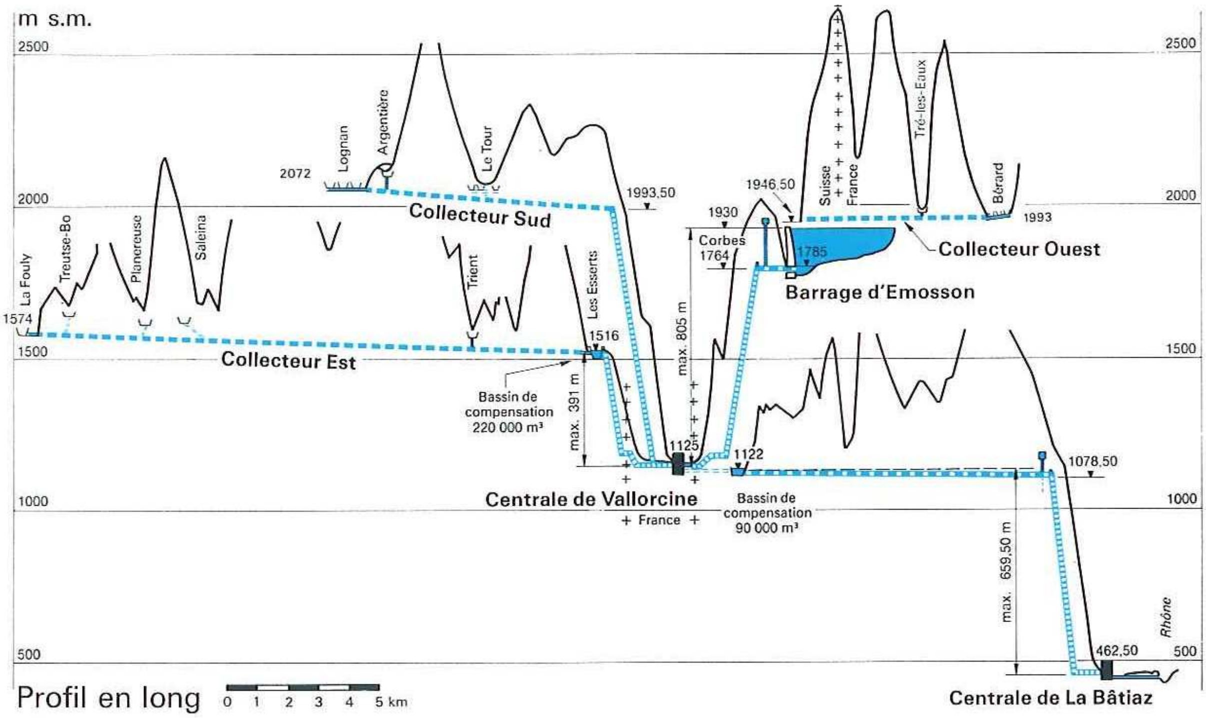


**Figure 3** Hydraulic layout of Electricité d'Emosson SA hydroelectric scheme.


**Figure 4** Power house of 170 MW La Bâtiaz HPP.

### 3.1. Power plant general description

The Hydro-Clone has been installed at La Bâtiaz HPP which is part of the Electricité d'Emosson hydroelectric complex. The 170 MW installed capacity comprises two Pelton turbine Units of 85 MW each, fed by an adduction system comprising an upper reservoir, a 9973 m long gallery of 3.5 m diameter, a surge tank with lower and higher expansion chambers, a 1253 m long inclined pressure shaft of 2.7 to 2.4 m diameter, and finally a manifold. Figure 5 presents the layout of the inclined pressure shaft. The main characteristics of the power plant are summarized in Table 1, and Figure 6 presents a cutting view of the power house itself.

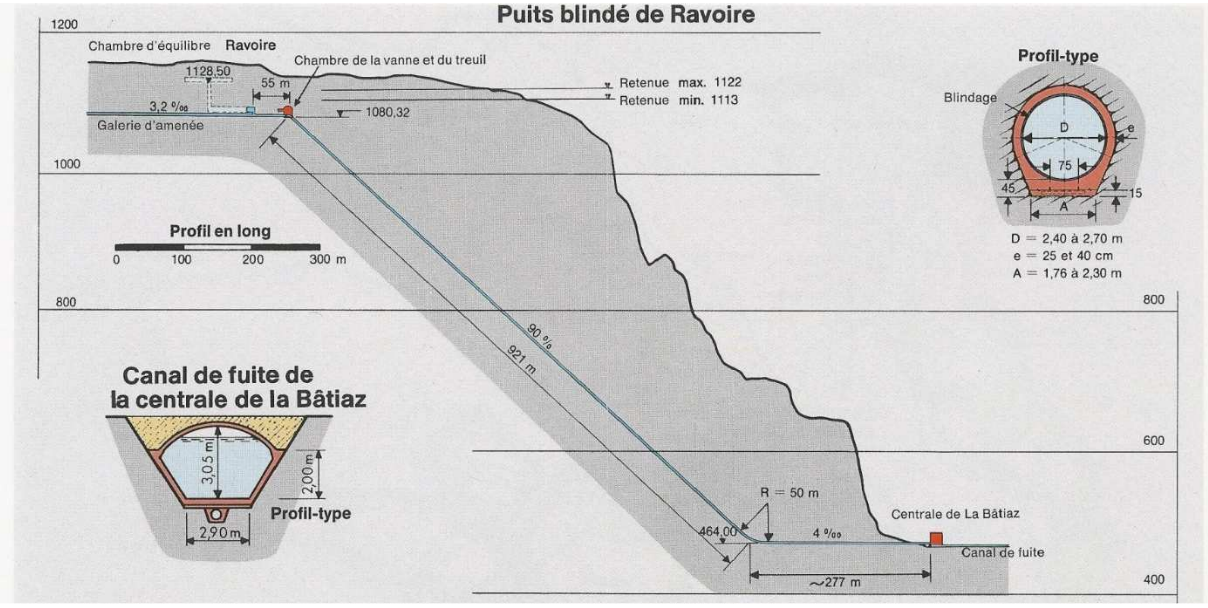


**Figure 5** La Bâtiaz pressure shaft layout.

**Table 1** La Bâtiaz power plant main characteristics.

| Description | Value |
|---|---|
| Installed capacity | 2x85 MW |
| Maximum gross head | 659.5 mWC |
| Total nominal discharge | 29 $m^3/s$ |
| Nominal rotational speed | 428.6 rpm |
| Number of injectors per unit | 5 |
| Pelton runner diameter | 2.36 m |
| Rotating axis orientation | Vertical |

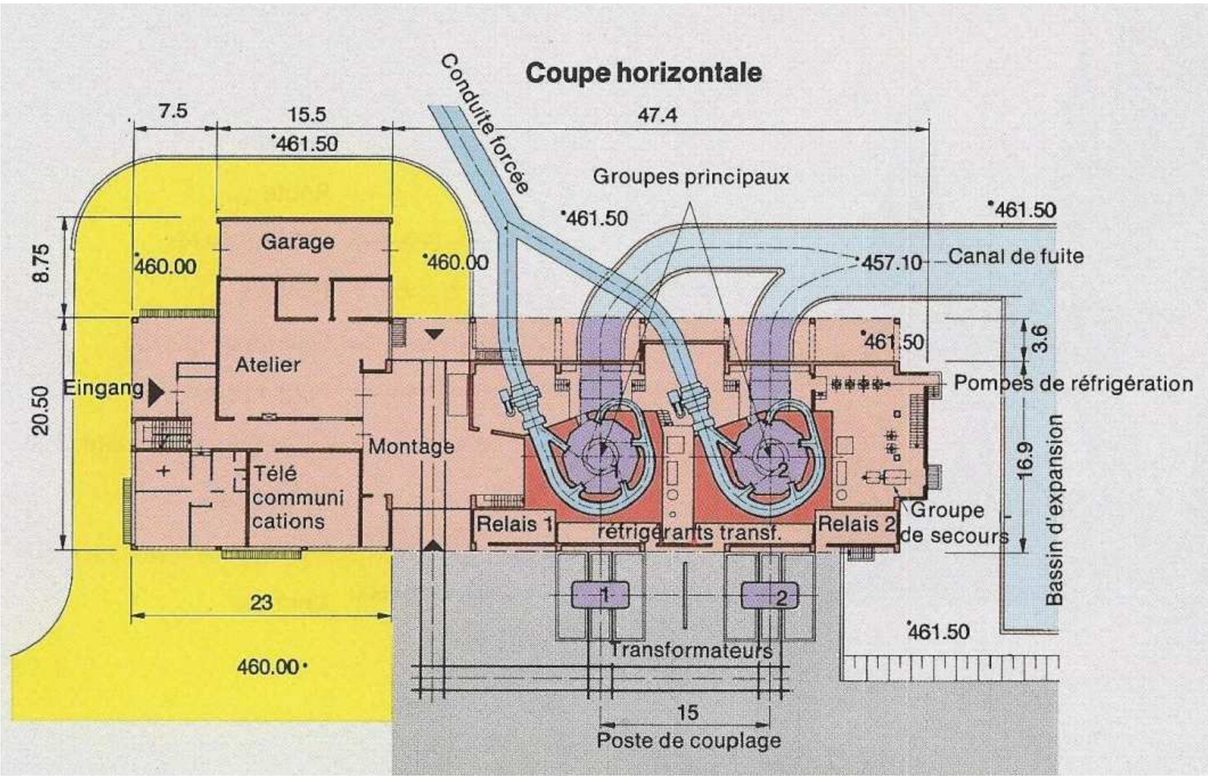


**Figure 6** Horizontal cutting view of 2x85 MW La Bâtiaz Pelton turbine Unit.

### 3.2. Power plant modelling

Figure 7 presents the SIMSEN model of the La Bâtiaz HPP, showing the different elements covered by the corresponding Hydro-Clone. The model comprises the upper reservoir, the headrace tunnel, the surge tank with upper and lower expansion chamber, the pressure shaft, the manifold and the two Pelton turbine Units. The turbines are modelled with their injector's characteristics, while active power is calculated according to unit efficiency hillcharts and generator efficiencies. The SIMSEN model accounts for water hammer, surge tank mass oscillation and Pelton turbine transients phenomena, see ANNEX 1 and [4], [5], [7].

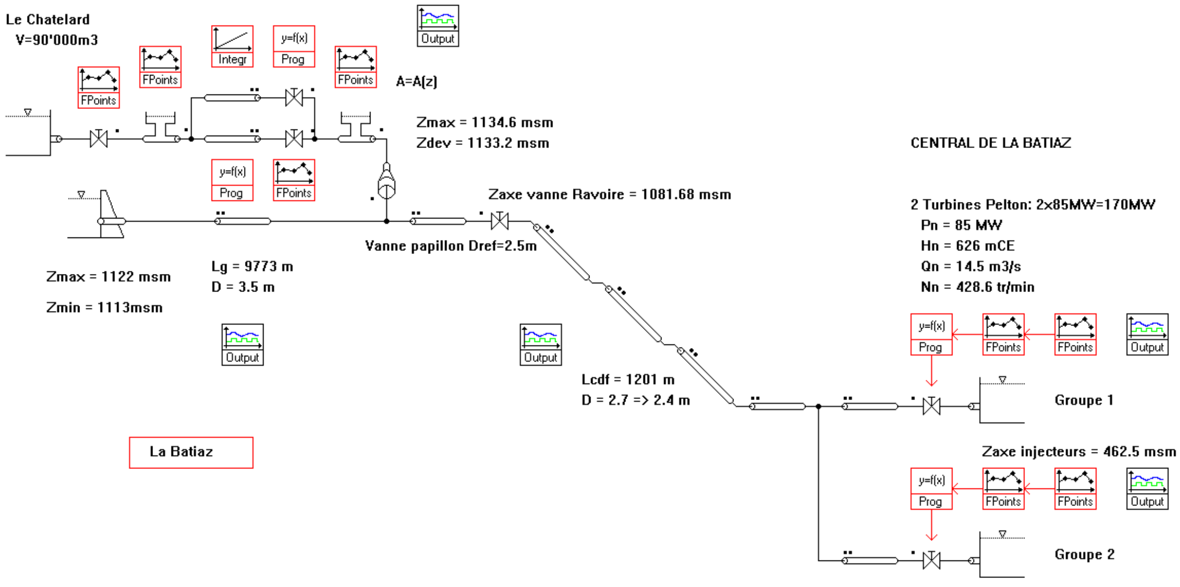


**Figure 7** La Bâtiaz power plant SIMSEN model.

## 4. Simulation model validation

On-site tests have been carried out to validate the SIMSEN model used by the Hydro-Clone. As such, an emergency shutdown on Unit 1 operating at maximum power of 85 MW has been performed using the Hydro-Clone. The SIMSEN simulation model is operated in Real-Time considering measured boundary conditions such as upper reservoir water level and Pelton turbine injector positions. In addition, pressure shaft piezometric head, surge tank water level and Pelton turbine active power were also acquired in Real-Time to perform on-line comparison with the corresponding simulated quantities. Figure 8 presents the data workflow of the Hydro-Clone, comprising acquisition carried out with the SCADA system at a sampling rate of 10 Hz, and transfer of measured quantities via the MODBUS protocol. Then, the measurements are transferred to the Hydro-Clone SIMSEN model of the La Bâtiaz HPP to setup boundary conditions, namely the upper reservoir water level and the Pelton turbine injector position, and to compare measured and simulated quantities.

Figure 9 presents the time evolution of the measured injector position of the two Units during the emergency shutdown and used as boundary conditions for the Real-Time simulation. Figure 10 and Figure 11 present respectively the comparison between the real-time simulated and measured pressure at the inlet of Unit 1 and the surge tank water level. Both feature very good agreement between simulation and measurements. It has to be outlined that all measurements have been obtained based on existing measurements made by the SCADA, and that no additional measurements were necessary to perform the Real-Time simulation and the model validation.

One of the advantages of the Hydro-Clone is that it provides lots of information on non-measured quantities that are usually very difficult or even impossible to measure. Indeed, Figure 12 presents the time evolution of 23 simulated pressures monitored along the pressure shaft. As the pressure at the inlet of Unit 1 and the surge tank water level feature good agreement, the simulated pressure along the pressure shaft can be considered as reliable and enable comparison with admissible values regarding minimum and maximum values. Figure 13 and Figure 14 present the envelopes of minimum and maximum pressure obtained by simulation respectively along the headrace tunnel and the pressure shaft. Such kind of analysis may easily be performed on-line to verify that the pressure remains within acceptable values.

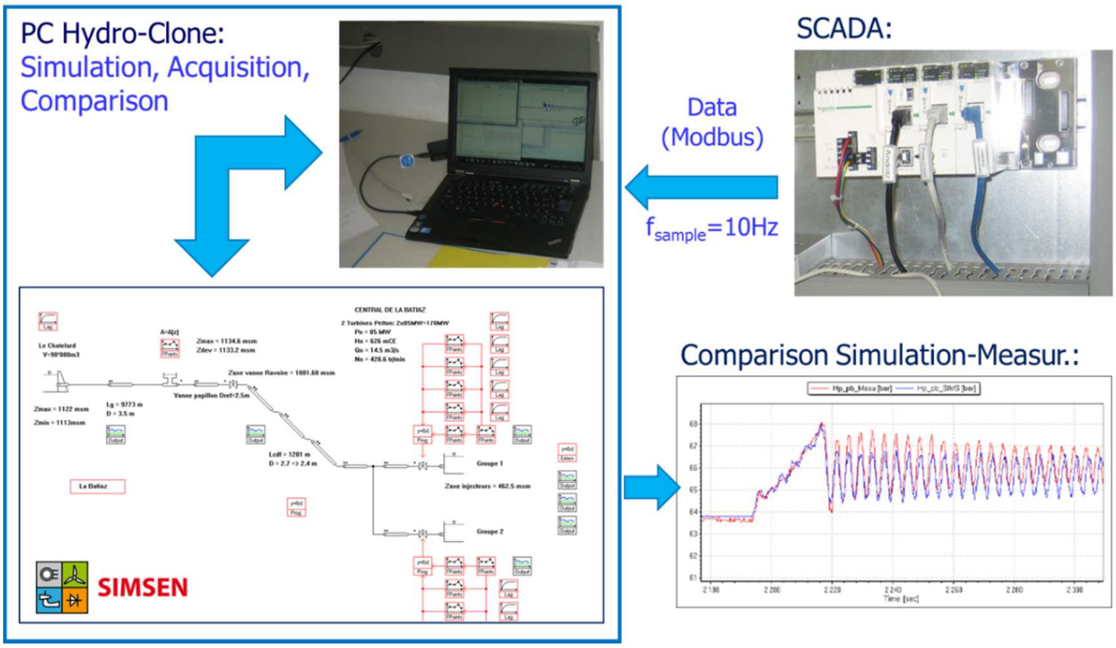


**Figure 8** Hydro-Clone as used for the validation of La Bâtiaz HPP.

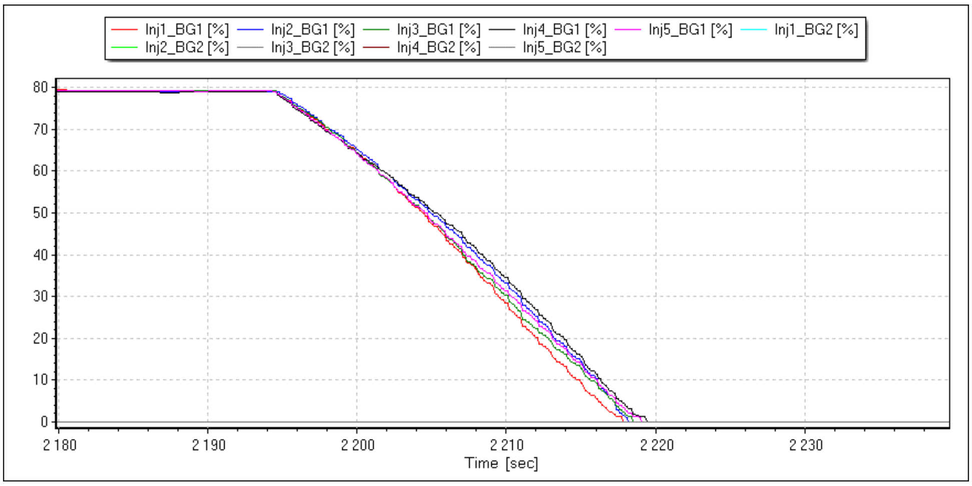


**Figure 9** Injectors position during emergency shutdown of Unit 1 of La Bâtiaz HPP.

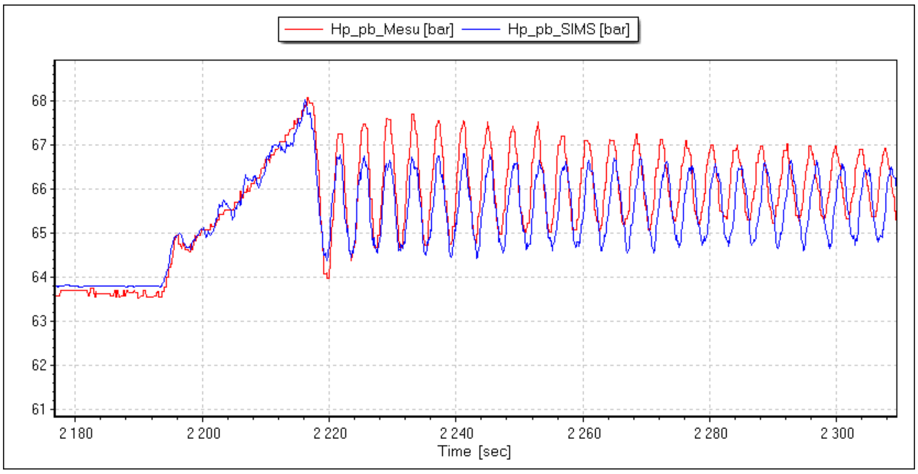


**Figure 10** Comparison between simulation results and on-site measurements of the pressure at inlet of Unit 1 resulting from emergency shutdown on Unit 1.

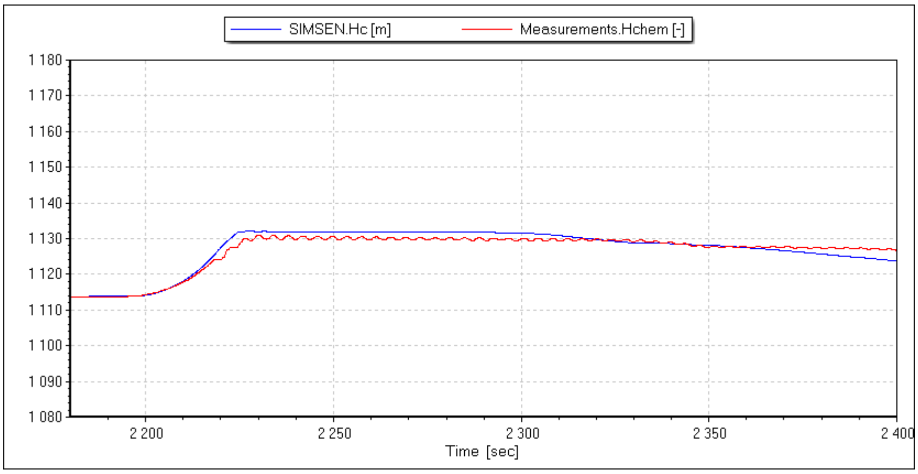


**Figure 11** Comparison between simulation results and on-site measurements of the surge tank water level resulting from emergency shutdown on Unit

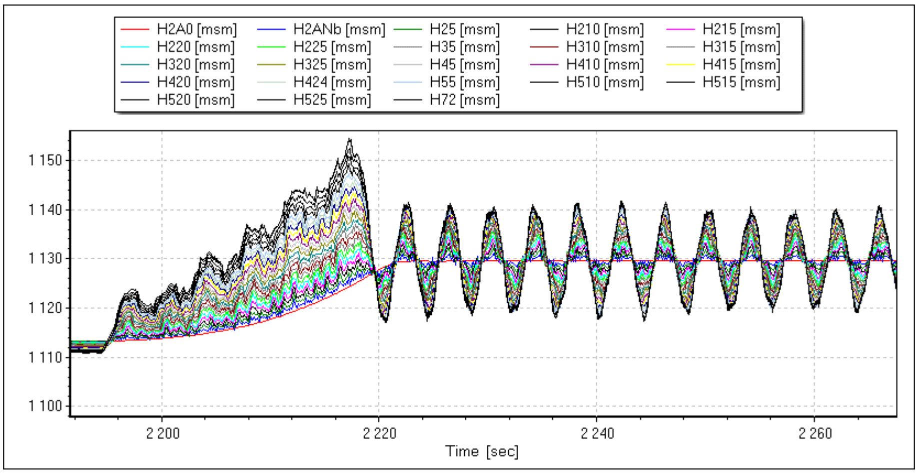


**Figure 12** Simulation result of the pressure along the pressure shaft.

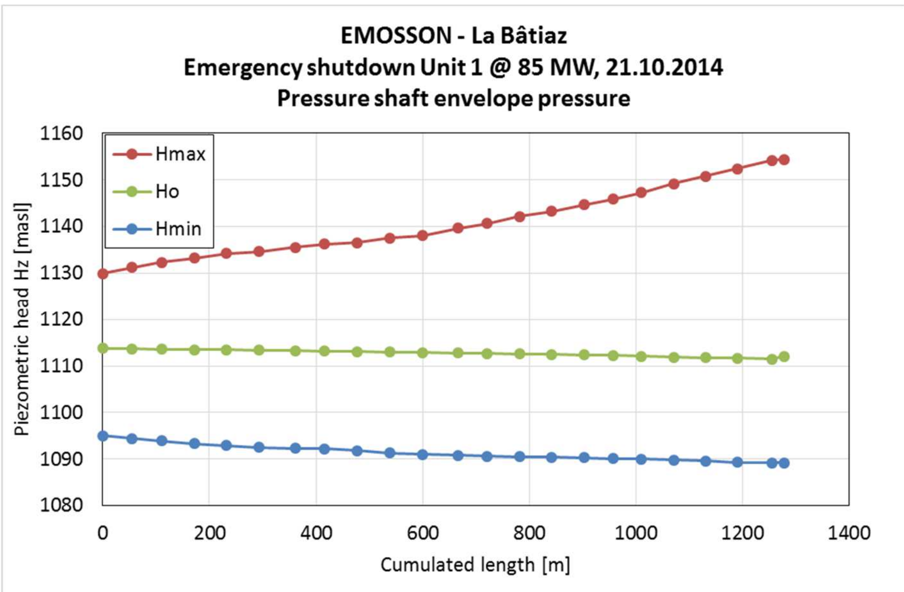


**Figure 13** Envelopes of maximum, minimum and initial pressures along the pressure shaft resulting from the emergency shutdown of Unit 1.

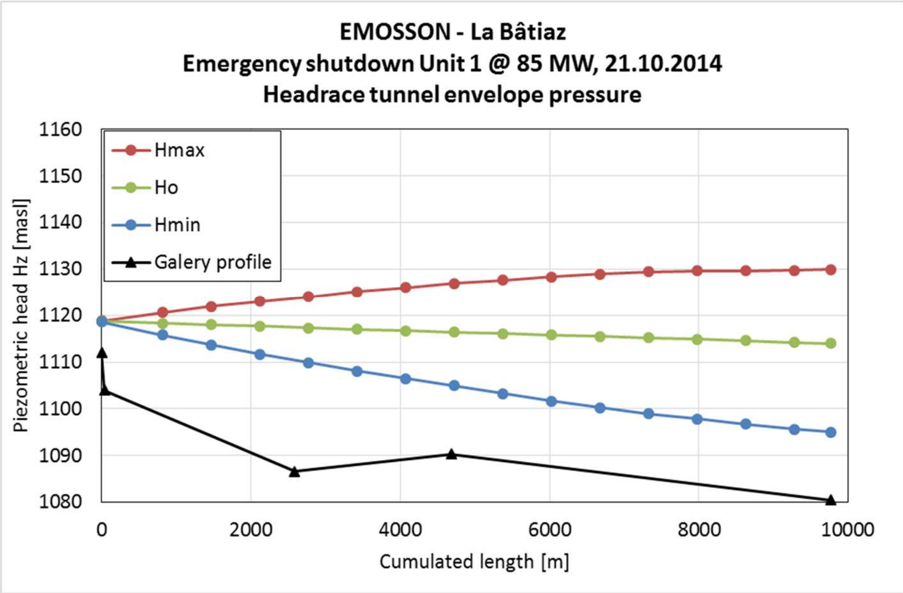


**Figure 14** Envelopes of maximum, minimum and initial pressures along the headrace tunnel resulting from the emergency shutdown of Unit 1.

## 5. Normal operation monitoring

Following sound validation of the SIMSEN simulation model, the Hydro-Clone was installed for long term simulation tests. Today, the system has been in continuous Real-Time operation since November 2014, *i.e.* since about 11 months. Figure 15 presents an extract of 10 days of continuous simulation results obtained with the Hydro-Clone at Unit 1, while Figure 16 presents a direct comparison of the resulting pressure at the inlet and of the active power of Unit 1, featuring very good agreement between simulation and measurements.

Figure 17 presents the analysis of an extract of the pressure at the inlet of turbine of Unit 1 at consecutive different time scales. By zooming into the time scale, this shows a very good agreement and points out a pressure peak event with an amplitude higher than the average values. Figure 18 (left) compares between simulated and measured active power of Unit 1, which shows good agreement. Figure 18 (right) presents the corresponding operating sequence of Unit 1, directly responsible for the recorded pressure peaks. These peaks appeared to be related to a switch from 5 injectors down to 3 injectors operation. Indeed, the reduction of the active power set point led to the automatic closure of 2 injectors, resulting in the re-opening of the three remaining injectors to follow the active power set point. The combination of fast closure and re-opening of the injectors is responsible for the pressure peak event. Such kind of events resulting from secondary control occur several times a day and directly contribute to pressure shaft fatigue. Knowing the pressure shaft mechanical characteristics, the survey of the pressure along the penstock using the Hydro-Clone allows to determine the evolution of the pressure shaft solicitations and to evaluate in real-time the corresponding pipe wall fatigue parameters.

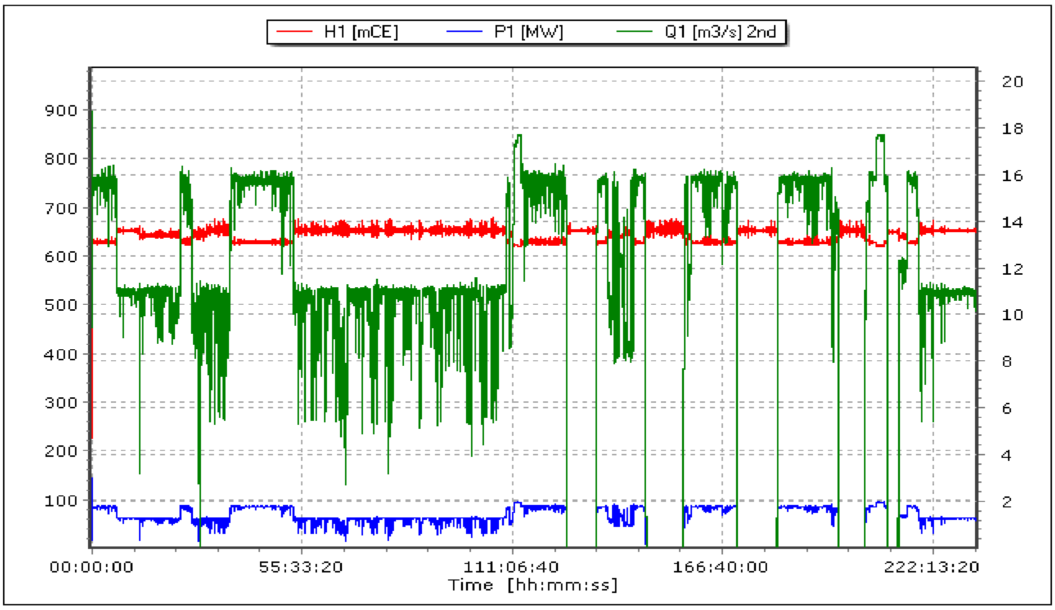


**Figure 15** Survey of net head H1, active power P1 and discharge Q1 of Unit 1 simulated over 10 days with the La Bâtiaz Hydro-Clone.

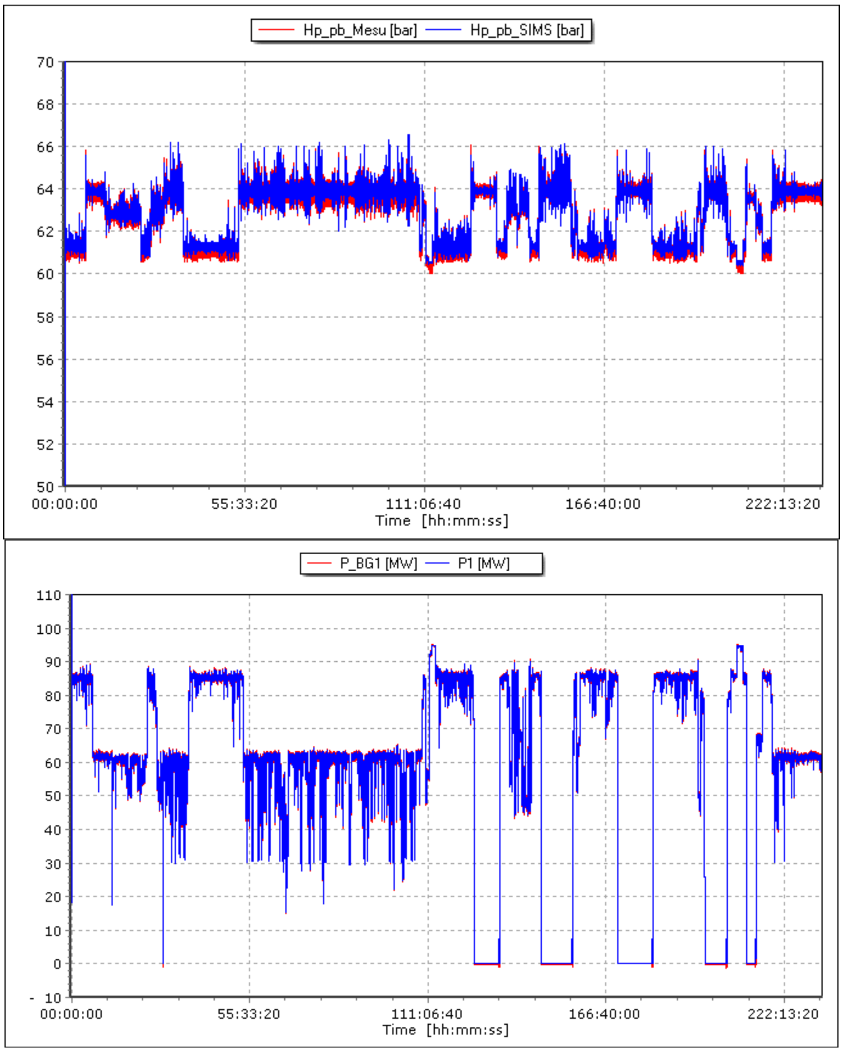


**Figure 16** Comparison between simulated and measured pressure at inlet of Unit 1 (top), and active power (bottom) over 10 days obtained with the La Bâtiaz Hydro-Clone.

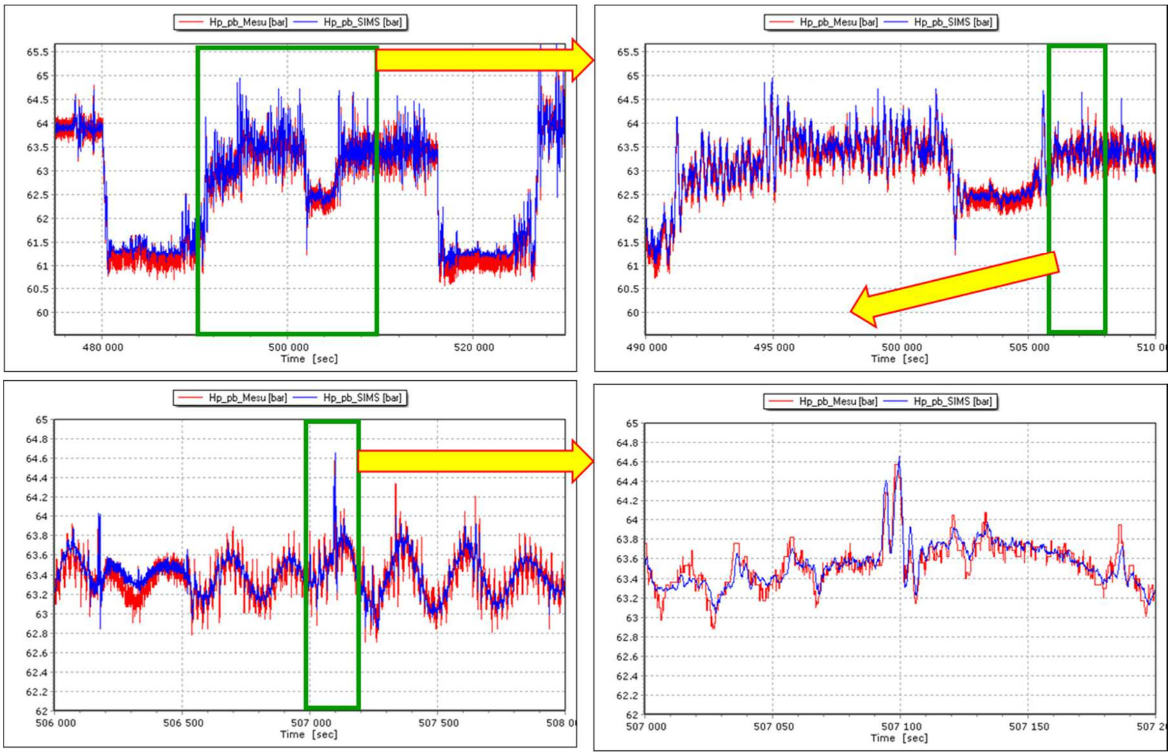


**Figure 17** Comparison between simulated and measured pressure at inlet of Unit 1 at different time scales obtained from the La Bâtiaz Hydro-Clone.

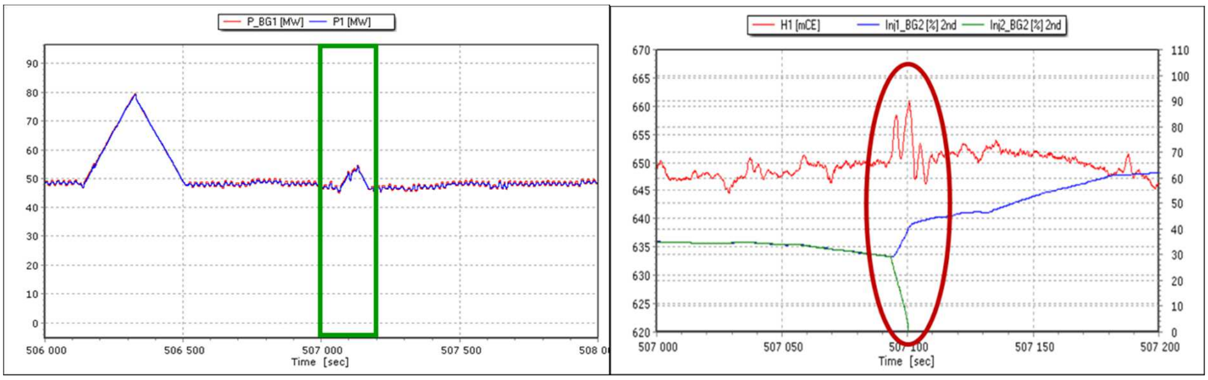


**Figure 18** Comparison between simulated and measured active power of Unit 1(left) and related simulation results of net head and injector position of Unit 1 (right) resulting from injector combination modification from 5 injectors to 3 injectors.

## 6. Conclusions

An innovative application of Real-Time Simulation Monitoring, defined as the Hydro-Clone, has been developed. The clone has been successfully tested and implemented for hydraulic applications at the 170 MW La Bâtiaz HPP, equipped with two Pelton turbines and part of the complex 380 MW Electricité d'Emosson SA hydroelectric scheme.

The tests performed at La Bâtiaz HPP enabled to validate the SIMSEN simulation model of the power plant throughout a Real-Time simulation of an emergency shutdown of one Unit at 85 MW. The Hydro-Clone, based on this validated simulation model, is in successful continuous operation since more than 11 months. These long term tests proof the reliability and accuracy of the developed Real-Time Simulation system. The key features of this system are the possibility to perform on-line diagnosis of the health state of the power plant based on 4 different possible alarms:

- Divergence between measurements and simulations to identify possible anomalies:
- Exceedance of admissible limit of measured quantity (classical monitoring);

- Exceedance of admissible limit of non-measurable quantity obtained from the simulation model in Real-Time (RTSM);
- Ahead-of-time projections of the state of the system (ATSM, what-if) to identify possible risks related to predefined scenarios such as emergency shutdown, unit loading, unexpected valve closure.

It is believed that such a system constitutes a key tool for sound and continuous assessment of HPP safety with respect to transient phenomena arising from normal and exceptional operating conditions. In addition, the Hydro-Clone allows follow-up and instant diagnosis of specific structural safety issues, such as for example potential fatigue of the different power plant components based on pressures, torques, and currents time histories obtained from the simulation model. When doing this, the reliability of the simulated quantities can be assessed in Real-Time from the comparison of simulated and measured monitored quantities. Furthermore, the Hydro-Clone can be easily installed without need for additional instrumentation and relying only on already measured quantities obtained directly from the existing SCADA system.

Since 2014, the Hydro-Clone has been successfully implemented on 3 different power plants in Switzerland equipped with Pelton turbines and storage pumps for one of the power plants. One of the applications was realized in the framework of the HYDRONET 2 research project, enabling to confirm the feasibility of hydroelectric Real-Time simulation of 23 MW Pelton generation Units, including the generator and transformer, see [2].

Recently, the Hydro-Clone services have already been extended to Francis turbines and pump-turbines. In the near future, they will be extended also to Kaplan turbines, allowing in this way a more systematic implementation in other power plants in Switzerland and abroad. By combining site-specific high-tech RTSM and ATSM capabilities with classical monitoring instrumentation, it is believed that the Hydro-Clone will significantly improve power plant safety by minimizing the number of safety concerns related to challenging electricity market demands.

## 7. Acknowledgements

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## 8. Nomenclature

- A: pipe cross section [$m^2$]
- $D_{ref}$: machine reference diameter [m]
- H: net head [m]
- Q: discharge [$m^3/s$]
- N: rotational speed [rpm]
- P: power [W]
- T: Torque [Nm]
- a: pipe wave speed [m/s]
- h: piezometric head $h=z+p/(\rho g)$ [m]
- h: per unit head $h=H/H_R$ [pu]
- g: gravity [$m/s^2$]
- n: per unit rotational speed $n=N/N_R$ [pu]
- p: static pressure [Pa]
- q: per unit discharge $q=Q/Q_R$ [pu]
- p: pressure [Pa]
- t: time [s]
- t: per unit torque $t=T/T_R$ [pu]
- u: per unit voltage [pu]
- y: turbine guide vane opening [-]
- *Z*: elevation above a datum [m]
- $_R$: subscript for rated

**References:**

[1] **European patent EP 2 801 879 A1**, "Hydroelectric power plant real-time monitoring system and method", 7.5.2013.

[2] **Han, M., Beguin, A., Nicolet, C., Kawkabani, B.,** "Advanced Condition Monitoring System for Synchronous Machines Based on Real-Time Simulation", Proceedings of the XXIth International Conference on Electrical Machines, Berlin, Germany – September 2-5, 2014, pp.: 1479-1485.

[3] **Jaeger, R. C.**, "Fluid transients in hydro-electric engineering practice ".Glasgow: Blackie, 1977.

[4] **Nicolet, C.,** "Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems", Thesis EPFL n° 3751, 2007, (http://library.epfl.ch/theses/?nr=3751).

[5] **Nicolet, C., Greiveldinger, B., Hérou, J.-J., Kawkabani, B., Allenbach, P., Simond, J.-J., Avellan, F., "**High Order Modeling of Hydraulic Power Plant in Islanded Power Network", IEEE Transactions on Power Systems, Vol. 22, Number 4, November 2007, pp.: 1870-1881.

[6] **Paynter, H. M.,** "Surge and water hammer problems". Transaction of ASCE, vol. 146, p 962-1009, 1953.

[7] **Sapin, A.,** "Logiciel modulaire pour la simulation et l'étude des systèmes d'entraînement et des réseaux électriques", Thesis EPFL n° 1346, 1995, (http://library.epfl.ch/theses/?nr=1346).

[8] **Souza, O.H., Jr., Barbieri, N., Santos, A.H.M.,** "Study of hydraulic transients in hydropower plants through simulation of nonlinear model of penstock and hydraulic turbine model", IEEE Transactions on Power Systems, vol. 14, issue 4, pp. 1269 – 1272, 1999.

[9] **Wylie, E. B. & Streeter, V.L.,** "Fluid transients in systems". Prentice Hall, Englewood Cliffs, N.J, 1993.

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**Guillaume GROS** graduated from the Institut national polytechnique de Grenoble, INPG, France, and received his Master in Power Engineering in 2000. He is managing director of Electricité d'Emosson SA, a Alpiq and EDF owned company which collects water from the Mont Blanc Massif. The water coming from the high valleys of the river Arve and Eau Noire in France, and, on the other hand, from Val Ferret and Trient Valley in Switzerland, is drained by three headrace tunnels and is routed to the artificial lake. With a mean gross head of 1400 m, the two stations of the scheme - Vallorcine (France, 210 MW) and La Bâtiaz (Switzerland, 190 MW) - annually generate 830 GWh. The water flows back to the Rhone river near Martigny.

## 9. ANNEXE 1: Modeling of the Hydraulic Machinery and Systems in SIMSEN

By assuming uniform pressure and velocity distributions in the cross section and neglecting the convective terms, the one-dimensional momentum and continuity balances for an elementary pipe filled with water of length *dx*, cross section *A* and wave speed *a*, see Figure 19, yields to the following set of hyperbolic partial differential equations [9]:

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{a^2}{gA} \cdot \dfrac{\partial Q}{\partial x} = 0 \\ \dfrac{\partial h}{\partial x} + \dfrac{1}{gA} \cdot \dfrac{\partial Q}{\partial t} + \dfrac{\lambda \left| Q \right|}{2gDA^2} \cdot Q = 0 \end{cases} \qquad (0)$$

The system (0) is solved using the Finite Difference Method with a 1st order center scheme discretization in space and a scheme of Lax for the discharge variable. This approach leads to a system of ordinary differential equations that can be represented as a T-shaped equivalent scheme [3], [6], [8] as presented in Figure 20. The RLC parameters of this equivalent scheme are given by:

$$R = \frac{\lambda \cdot \left| \overline{Q} \right| \cdot dx}{2 \cdot g \cdot D \cdot A^2} \qquad L = \frac{dx}{g \cdot A} \qquad C = \frac{g \cdot A \cdot dx}{a^2} \qquad (0)$$

Where λ is the local loss coefficient. The hydraulic resistance R, the hydraulic inductance L, and the hydraulic capacitance C correspond respectively to energy losses, inertia and storage effects.

The model of a pipe of length *L* is made of a series of $n_b$ elements based on the equivalent scheme of Figure 20. The system of equations relative to this model is set-up using Kirchoff laws. The model of the pipe, as well as the models of valve, surge tank, hydraulic turbines, etc, are implemented in the EPFL software SIMSEN developed for the simulation of the dynamic behavior of hydroelectric power plants, [4], [7]. The time domain integration of the full system is achieved in SIMSEN by a Runge-Kutta 4$^{th}$ order procedure.

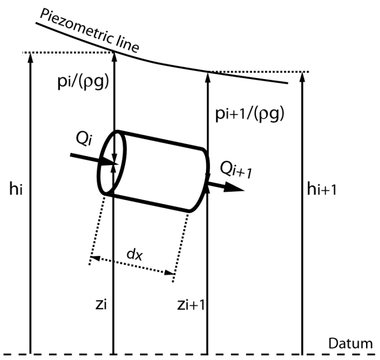


**Figure 19** Elementary hydraulic pipe of length dx.

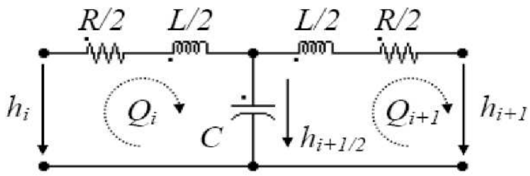


**Figure 20** Equivalent circuit of an elementary pipe of length dx.

The modeling approach based on equivalent schemes of hydraulic components is extended to all the standard hydraulic components such as valve, surge tanks, air vessels, cavitation development, Francis pump-turbines, Pelton turbines, Kaplan turbines, pump, etc, see [4]. The hydraulic machines are modelled with 4 quadrants characteristics defined by speed factor $N_{11}$, the discharge factor $Q_{11}$, and the torque factor $T_{11}$ defined as follows:

$$N_{11} = \frac{N \cdot D_{ref}}{\sqrt{H}} \qquad Q_{11} = \frac{Q}{{D_{ref}}^2 \cdot \sqrt{H}} \qquad T_{11} = \frac{T}{{D_{ref}}^3 \cdot H} \qquad (0)$$