Real-time simulation monitoring system for hydro plant transient surveys

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An innovative system for real-time simulation monitoring is presented, known as 'Hydro-Clone'. It was tested at the 170 MW La Bâtiaz hydro plant, equipped with Pelton units, with good results. This led to a broadening of its application at other types of plant. It is felt that the system will play a significant role in reducing safety concerns at hydro plants.

Simulation of a hydro plant by 'cloning' makes it possible to detect undesirable phenomena, such as penstock or gallery overpressures, head loss increases, decreases in efficiency, surge tank limits, start-up and shut-down issues, unexpected cavitation and possible water column separations, air intake, and unwanted valve closures. Furthermore, a clone is able to minimize the risk of potential imminent harmful behaviour of the plant, 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 plant. By combining RTSM and ATSM in real-time, it is believed that the newly developed system, known as Hydro-Clone, can be a valuable numerical asset for hydro plant owners to improve powerplant safety.

The so-called Hydro-Clone comprises: a simulation model for a hydro powerplant; a real-time management system linking the actual powerplant with the clone, or virtual powerplant; a monitoring system with transient phenomena-based alarms; and, a database system with remote access. By appropriate calibration of the simulation model and real-time use of in-situ measurements, the transient behaviour of the powerplant can be instantaneously replicated, generating a representative numerical copy of the real powerplant, known as 'the clone'.

Long-term tests carried out at La Bâtiaz hydro plant, since 2014, have confirmed the reliability of real-time transient computations of complex waterways, including, for example, transient pressures, discharges, the active power of the various units and surge tank water level oscillations.

1. Background to the development

Hydropower plants play an important role for grid stability because of their operational flexibility and 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. Modernized control systems allow for faster response of the hydropower units, which are increasingly being operated by remote control. The installed capacity of hydro plants is also frequently increased during rehabilitation, resulting in an increased discharge in the adduction system. As a result, most existing hydropower plants are subjected to new operating conditions and sequences which were not foreseen during their design. Also, the significant increase in load variations and material induced stress levels enhances fatigue in ageing components. Thus, the accurate prediction of transient behaviour in hydro plants is becoming more difficult because of the variety of possible scenarios and unexpected events or sequences, which need to be considered.

To address the issue of sound transient surveying, an innovative application of real-time simulation monitoring (RTSM), hydro-cloning, has been developed by Power Vision Engineering. Since 2014, this system has been successfully implemented at the 170 MW La Bâtiaz hydro plant, 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 powerplant, a real-time management system linking the actual powerplant with the clone or virtual powerplant, a monitoring system with transient phenomena-based alarms, and a database 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 plant is instantaneously replicated, generating a representative numerical copy of the real powerplant, called the clone.

The simulation model of the La Bâtiaz plant includes the upper reservoir, the 10 000 m-long gallery, the surge tank, the 1200 m-long penstock, the manifold and the two 85 MW vertical axis Pelton turbines with five injectors each. This simulation model, based on the SIMSEN software, can take into account water-hammer phenomena in the gallery and in the penstock, surge tank mass oscillations and any transient behaviour of the Pelton units. Long-term in-situ testing showed the ability of the Hydro-Clone to replicate precisely in real-time the transient pressures measured at the top and 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, the active power of the various units and surge tank water level oscillations. Long-term cloning of the powerplant makes it possible to detect the undesirable phenomena as described above.

2. The Hydro-Clone

2.1 General description

The system is a soundly calibrated and validated numerical copy of a hydro plant, that is, a numerical

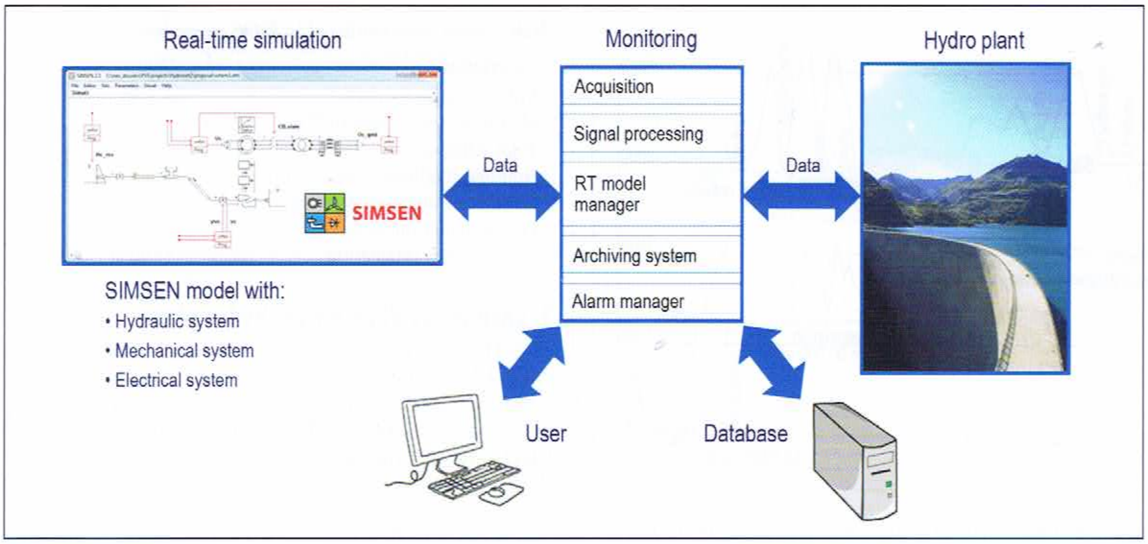


Fig. 1. Concept of the Hydro-Clone system, based on real-time simulation of a hydro plant.

clone. This system, subject to patent [see European Patents, 2013[5]], makes it possible to diagnose the health of a hydro plant continuously by real-time numerical cloning of the major hydraulic and electrical components of the plant, using the SIMSEN software [Nicolet, 2007[1]; Sapin, 1995[2]], and existing key monitoring points. As shown in Fig. 1, the Hydro-Clone comprises the following components:

• A calibrated and validated SIMSEN simulation model of the hydro plant, 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; and, 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's real-time simulation of the real hydro plant; data processing and diagnosis of the powerplant's health; provision of 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 plant; and, communication with tailor-made archival storage system.
• A tailor-made archival storage and related database system, making it possible to: archive simulated and measured quantities; display and analyse previous results; provide contingency alarms; and, update and enhance the clone functioning.

2.2 Function of the Hydro-Clone

As shown in Fig. 2, the numerical simulation model benefits from measured boundary conditions, such as the upper and lower reservoir water levels, guide-vane/injector openings, voltage of the grid 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 makes it possible to:

• understand at any time the condition 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 a lack or defect in measurements;
• detect hydraulic/electric anomalies in real time by 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; and,
• carry out 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 shown in Fig. 2, the Hydro-Clone provides four types of alarms, based on the following:

• 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

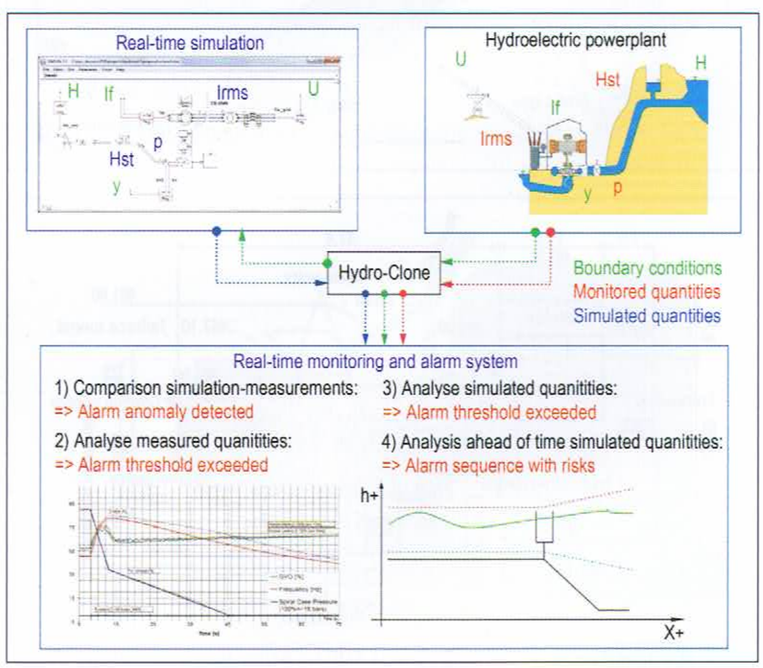


Fig. 2. Data exchange of Hydro-Clone between the real-time simulation model and the acquisition system, including related alarms.

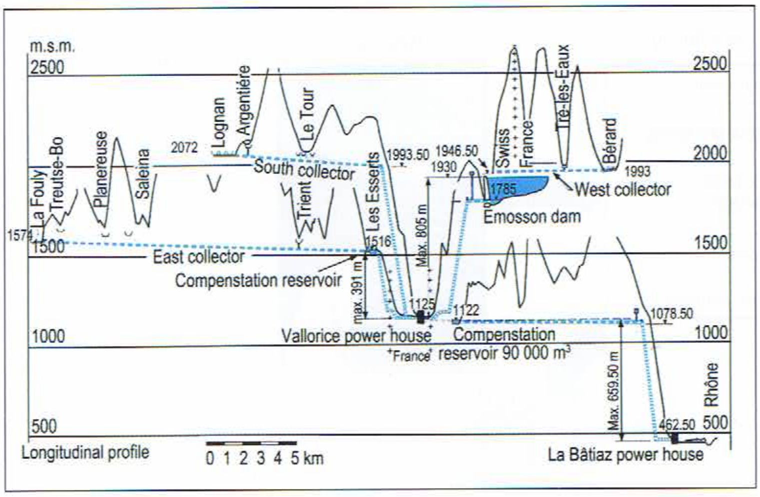


Fig. 3. Hydraulic layout of Electricité d'Emosson SA hydroelectric scheme.

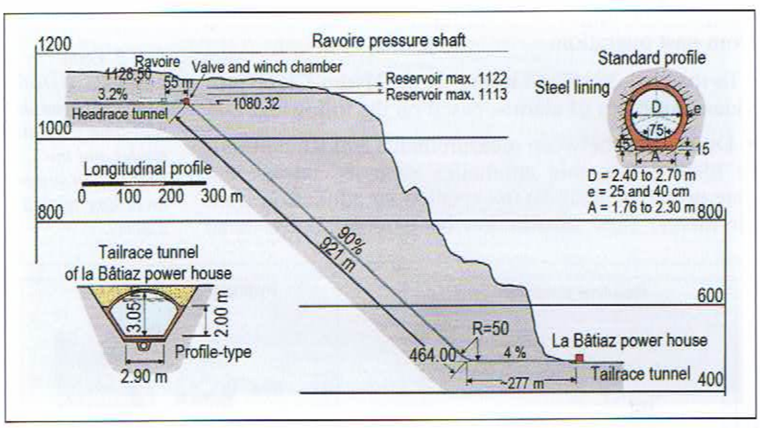
Fig. 4. Layout of the pressure shaft at La Bâtiaz.

loss increase; water column separation; conduit breakdown; surge tank sediment deposit.

• Exceedance of the admissible limit of a measured quantity (that is, 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; and, extreme current or voltage.

• Ahead-of-time projections of the state of the system (what-if), to identify possible risks related to predefined scenarios such as emergency shutdown, unit loading, or unexpected valve closure.



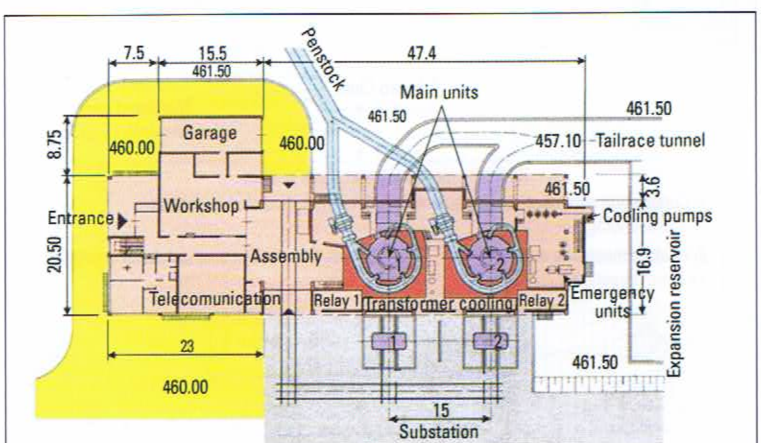


Fig. 5. Horizontal cross section of the 2 × 85 MW La Bâtiaz Pelton powerplant.

Table 1: Main characteristics of La Bâtiaz powerplant

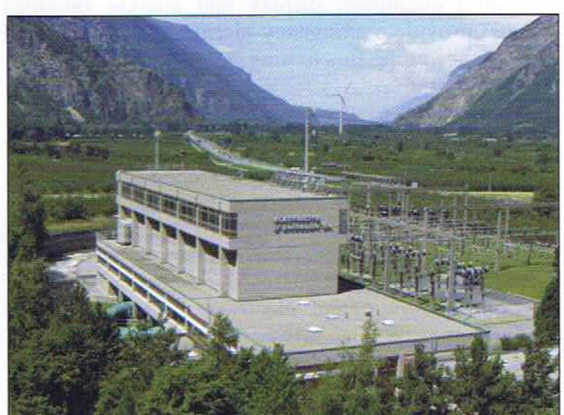
Description	Value
Installed capacity (MW)	2 × 85
Maximum gross head (mWC)	659.5
Total nominal discharge m³/s	29
Nominal rotational speed (rpm)	428.6
Number of injectors per unit	5
Pelton runner diameter (m)	2.36
Rotating axis orientation	Vertical

3. Case study of La Bâtiaz hydro plant

The Hydro-Clone has been tested, in collaboration with Electricité d'Emosson SA (jointly owned by Alpiq and EDF), since 2014 at the 170 MW La Bâtiaz plant, Switzerland, see Fig. 3. The hydraulic works of Electricité d'Emosson collect water from the Mont Blanc Massif, which is channelled into the Emosson reservoir, with a maximum water level at el. 1930. Water coming from the high valleys of the river Arve and Eau Noire in France, and from Val Ferret and Trient Valley, feeds into three headrace tunnels. The water is conveyed by gravity through the south and west collectors on the French side, to the artificial lake. The volumes from the Swiss side arrive through the eastern supply line. After passing through the compensation basin of Esserts, the water may be pumped by the Vallorcine power station to Emosson and/or may be turbined to the Châtelard reservoir, depending on the natural inflows and electricity management.

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

The La Bâtiaz plant, where the Hydro-Clone has been installed, is equipped with two 85 MW Pelton units, fed by an adduction system comprising an upper reservoir, a 9973 m-long gallery with a 3.5 m diameter, a surge tank with lower and higher expansion chambers, a 1253 m-long inclined pressure shaft with a diameter of 2.7 to 2.4 m, and a manifold. Fig. 4 shows the layout of the inclined pressure shaft. The



The powerhouse of 170 the MW La Bâtiaz hydro plant.

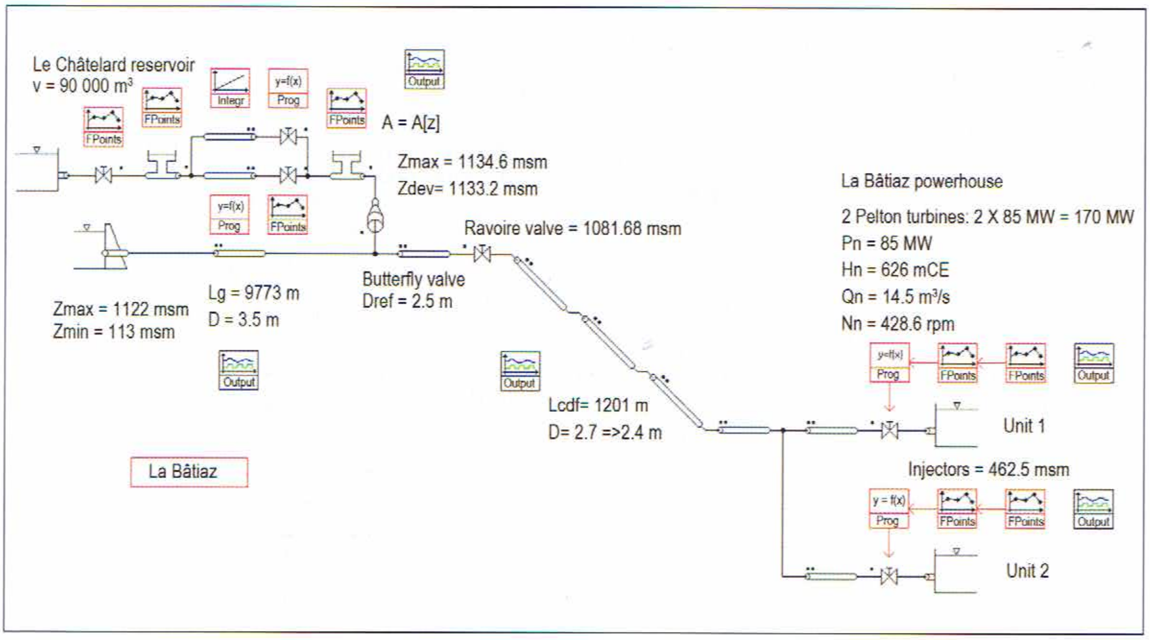


Fig. 6. The SIMSEN model.

main characteristics of the plant are summarized in Table 1, and Fig. 5 is a cross section of the powerhouse.

3.1 Modelling of the plant

Fig. 6 presents the SIMSEN model of La Bâtiaz powerplant, showing the various elements covered by the corresponding Hydro-Clone. The model includes the upper reservoir, the headrace tunnel, the surge tank with upper and lower expansion chamber, the pressure shaft, the manifold and the two Pelton units. The turbines are modelled with their injectors' characteristics, while active power is calculated according to unit efficiency hillcharts and generator efficiencies. The SIMSEN model accounts for waterhammer, surge tank mass oscillation and Pelton turbine transients phenomena, [Nicolet, 2007[1]; Nicolet *et al*, 2007[3]; Sapin, 1995[2]].

4. Validation of the simulation model

On-site tests have been carried out to validate the SIMSEN model used by the Hydro-Clone. An emergency shutdown of 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, taking into account 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, so that an on-line comparison could be made with the corresponding simulated quantities. Fig. 7 shows the data workflow of the Hydro-Clone, comprising acquisition carried out with the SCADA system at a sampling rate of 10 Hz, and the transfer of measured quantities via the MODBUS protocol.

The measurements are transferred to the Hydro-Clone SIMSEN model of the La Bâtiaz plant to setup boundary conditions, namely the upper reservoir water level and the Pelton turbine injector position, and to compare measured and simulated quantities.

Fig. 8 shows the evolution time of the measured injector position of the two units during the emergency shutdown, used as boundary conditions for the real-time simulation. Figs. 9 and 10 present 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 should be mentioned that all measurements were obtained based on existing ones from the SCADA system, and no additional measurements were necessary to carry out the real-time simulation and the model validation.

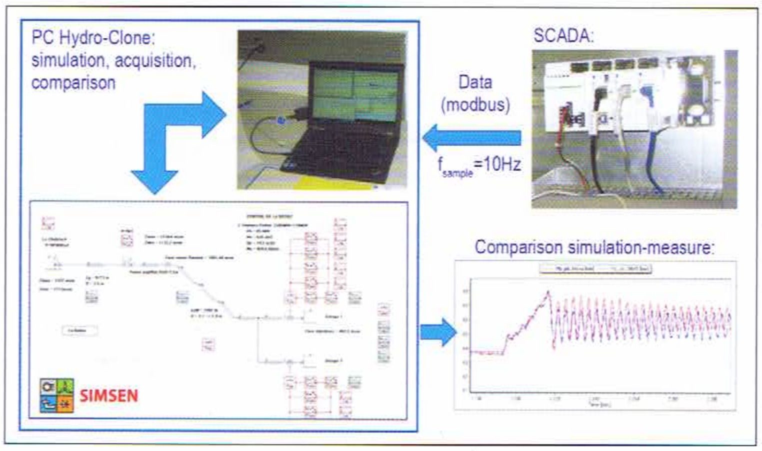


Fig. 7. Hydro-Clone, as used for the validation of La Bâtiaz.

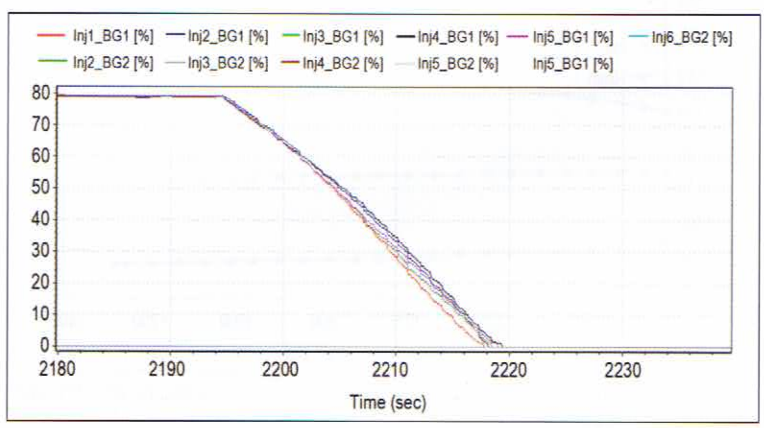


Fig. 8. Injectors position during emergency shutdown of unit 1 at La Bâtiaz.

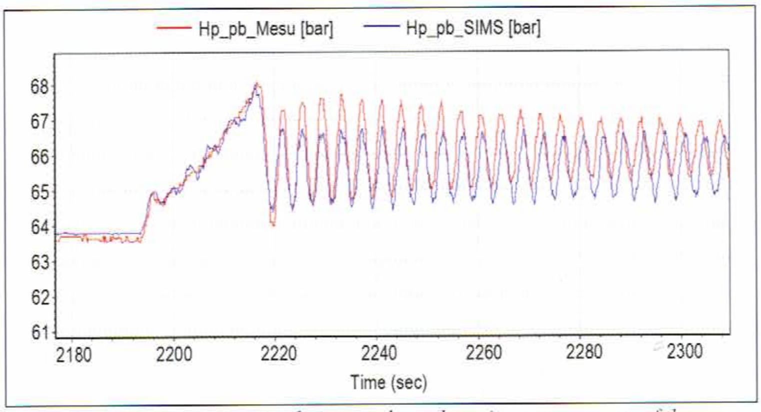


Fig. 9. Comparison between simulation results and on-site measurements of the pressure at inlet of unit 1 resulting from emergency shutdown on unit 1.

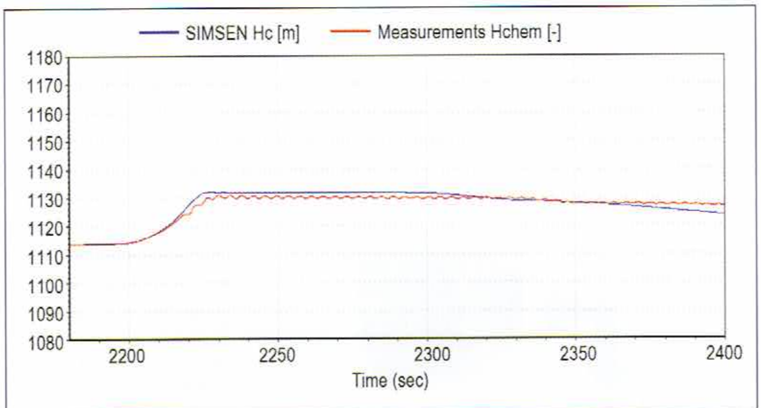


Fig. 10. Comparison between simulation results and on-site measurements of the surge tank water level resulting from emergency shutdown on unit 1.

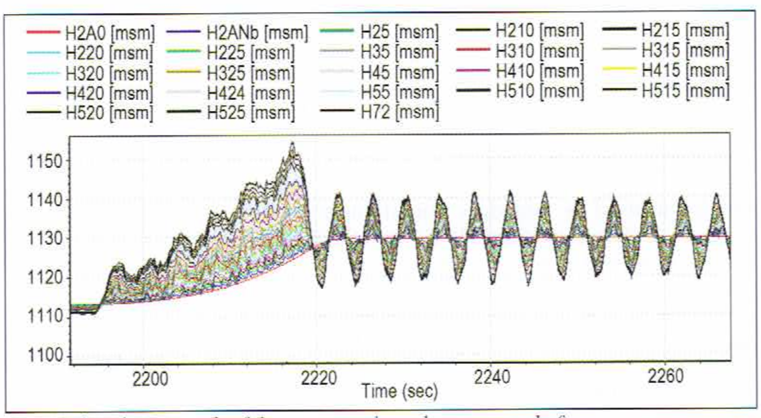


Fig. 11. Simulation result of the pressure along the pressure shaft.

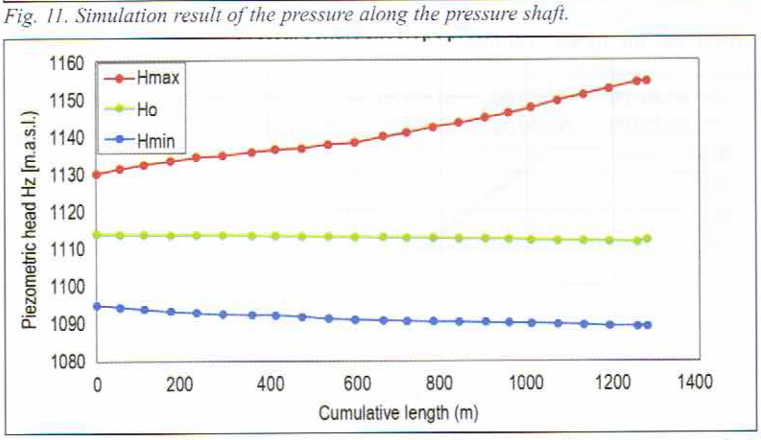


Fig 12. Envelopes of maximum, minimum and initial pressures along the pressure shaft resulting from the emergency shutdown of unit 1.

One of the advantages of the Hydro-Clone is that it provides a great deal of information on non-measured quantities that are usually very difficult or even impossible to measure. For example, Fig. 11 shows 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 allow for a comparison with admissible values regarding the minimum and maximum values. Figs. 12 and 13 show the envelopes of minimum and maximum pressure obtained by simulation, respectively, along the headrace tunnel and the pressure shaft. This kind of analysis can easily be done on-line, to verify that the pressure remains within acceptable values.

5. Monitoring normal operation

Following sound validation of the SIMSEN simulation model, the Hydro-Clone was installed for long-term simulation tests. The system has now been in continuous real-time operation since November 2014 (about 11 months at the time of writing). Fig. 14 presents an extract from the simulation results for 10 days of continuous obtained with the Hydro-Clone at unit 1, and Fig. 15 gives a direct comparison of the resulting pressure at the inlet and of the active power of unit 1, demonstrating very good agreement between simulation and measurements.

Fig. 16 gives the analysis of an extract of the pressure at the inlet of the turbine of unit 1 at consecutive time scales. Reviewing the time scale, one can find very good agreement, and a pressure peak event can be observed with an amplitude higher than the average values. Fig. 17 (left) compares the simulated and measured active power of unit 1, which shows good agreement. The right side of Fig. 17 shows the corresponding operating sequence of Unit 1, directly responsible for the recorded pressure peaks. These peaks appeared to be related to a switch from five to three injectors operating. Indeed, the reduction in the active power set point led to the automatic closure of two 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 was responsible for the pressure peak event. Such events resulting from secondary control occur several times a day, and directly contribute to pressure shaft fatigue. Knowing the mechanical characteristics of the pressure shaft, the survey of the pressure along the penstock using the Hydro-Clone made it possible to determine the evolution of the pressure shaft induced stresses, and to evaluate in real time the corresponding pipe wall fatigue parameters.

6. Conclusions

The tests carried out at La Bâtiaz made it possible to validate the SIMSEN simulation model of the powerplant throughout a real-time simulation of an emergency shutdown of one unit at 85 MW. The Hydro-Clone, based on this validated simulation model, has been in successful continuous operation for more than 11 months. These long-term tests have proved the reliability and accuracy of the system. The key features of this system are the possibility to perform on-line diagnosis of the status of the powerplant based on four possible alarms:

• divergence between measurements and simulations to identify possible anomalies;
• exceedance of admissible limit of measured quantity (classical monitoring);
• exceedance of the admissible limit of a non-measurable quantity obtained from the simulation model in real time (RTSM); and,
• ahead-of-time projections of the state of the system (ATSM, what-if) to identify possible risks related to pre-defined scenarios such as emergency shutdown, unit loading, or unexpected valve closure.

It is believed that such a system constitutes a key tool for sound and continuous assessment of hydro plant safety with respect to transient phenomena arising from normal and exceptional operating conditions. In addition, the Hydro-Clone allows for follow-up and instant diagnosis of specific structural safety issues, such as potential fatigue of the powerplant components based on pressures, torques, and current time histories obtained from the simulation model. The reliability of the simulated quantities can be assessed in real time from a comparison of simulated and measured monitored quantities. Furthermore, the Hydro-Clone can easily be installed without the need for additional instrumentation, and it is possible to rely only on values already measured using the existing SCADA system.

Since 2014, the Hydro-Clone has been successfully implemented at three powerplants in Switzerland equipped with Pelton turbines, and storage pumps at one of the plants. One of these applications was within the framework of the HYDRONET 2 research project, making it possible to confirm the feasibility of real-time simulation of 23 MW Pelton units, including the generator and transformer, [Han *et al*, 2014[4]].

Recently, the Hydro-Clone application was extended to Francis turbines and pump-turbines. In the near future, the system will also be used for Kaplan turbines, thus allowing for a more systematic implementation at other powerplants in Switzerland and other countries. By combining site-specific high-tech RTSM and ATSM capabilities with classical monitoring instrumentation, it is believed that the Hydro-Clone will significantly improve powerplant safety by minimizing the number of safety concerns related to challenging electricity market demands. ◊

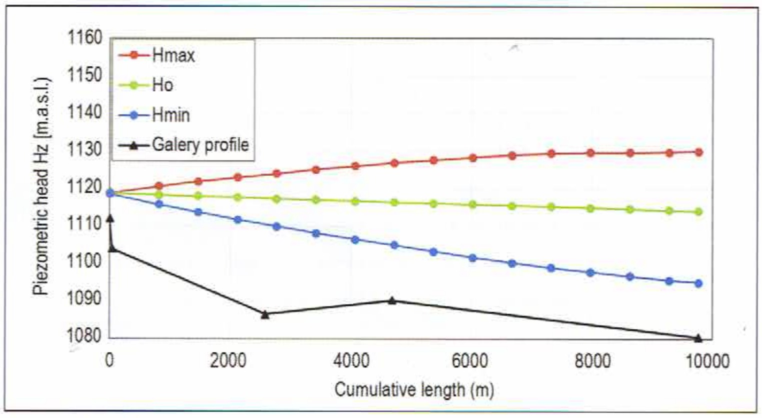


Fig. 13. Envelopes of maximum, minimum and initial pressures along the headrace tunnel resulting from the emergency shutdown of unit 1.

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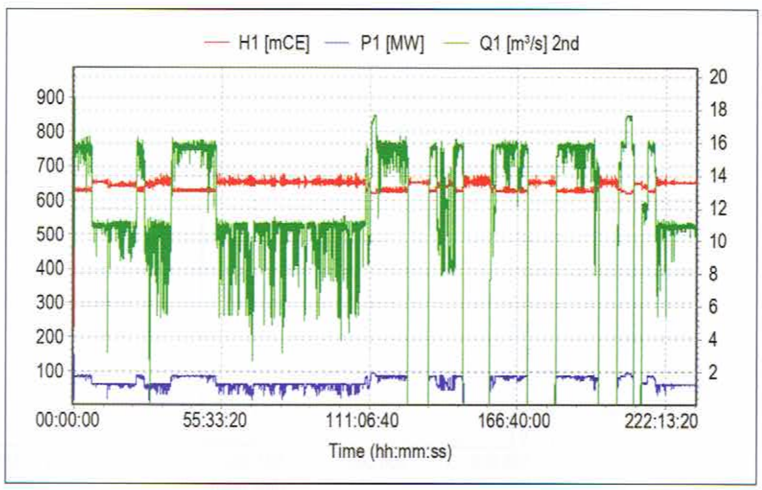

Fig. 14. Survey of net head H1, active power P1 and discharge Q1 of unit 1 simulated over 10 days with the La Bâtiaz Hydro-Clone.

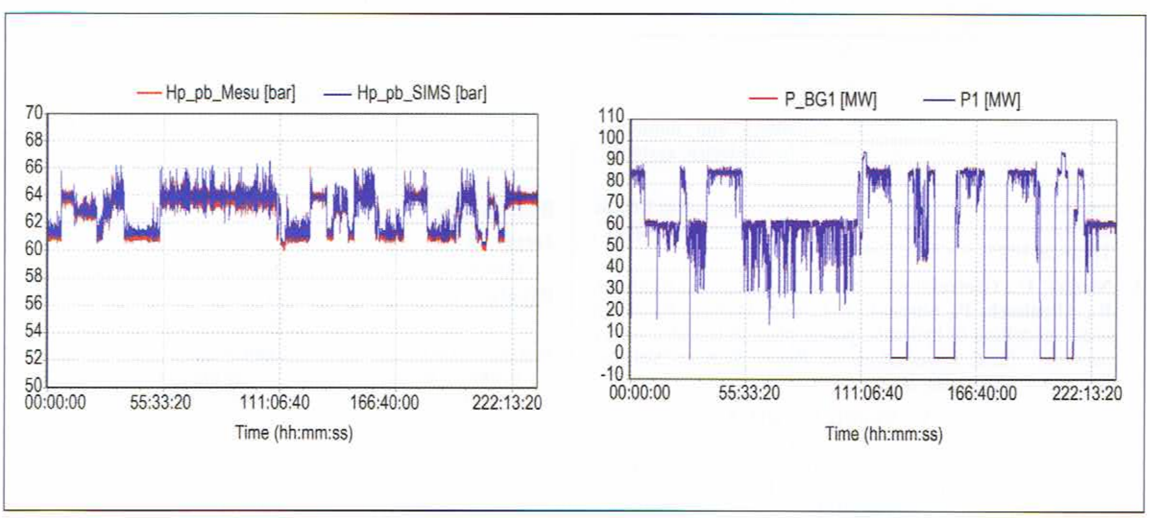

Fig. 15. Comparison between simulated and measured pressure at inlet of unit 1 (top), and active power (bottom) over 10 days obtained with the La Bâtiaz Hydro-Clone.

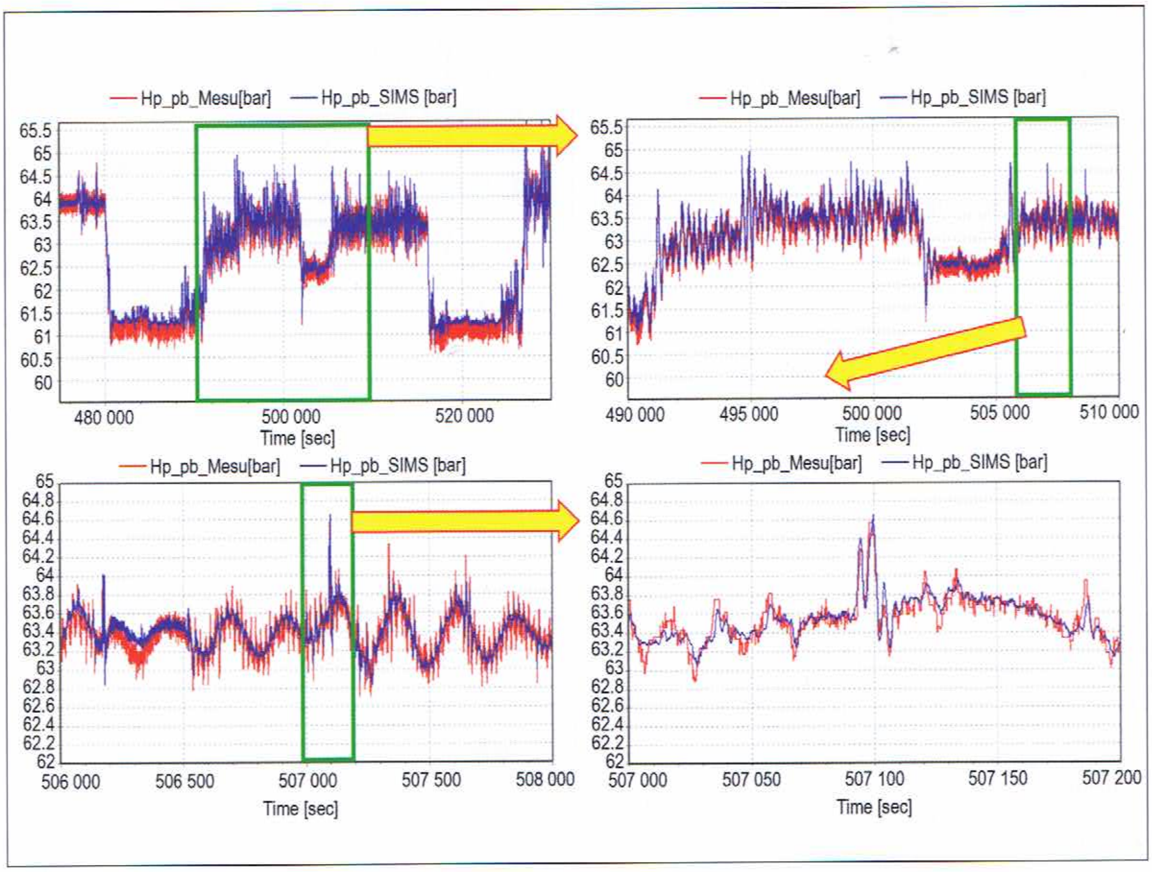

Fig. 16. Comparison between simulated and measured pressure at inlet of unit 1 at different time scales obtained from the La Bâtiaz Hydro-Clone.

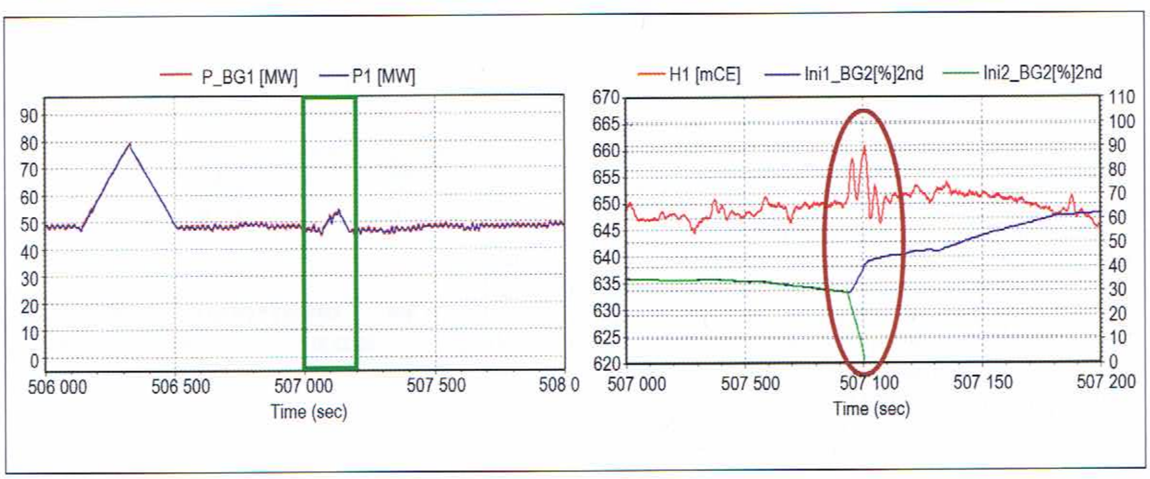

Fig. 17. Comparison between simulated and measured active power of unit 1 (left) and related simulation results of net head and injector position of unit 1 (right) resulting from injector combination modification from 5 to 3 injectors.

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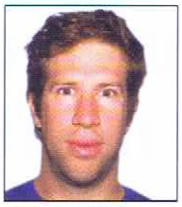

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