New surge tank commissioning at the Hongrin-Léman pumped-storage plant by real time simulation monitoring

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Introduction

FMHL (Forces Motrices Hongrin-Léman SA) is the owner's company that belongs to the shareholders Romande Energie SA, Alpiq Suisse SA, Groupe E SA and City of Lausanne. Alpiq, as owners' representative, is in charge of the supervision of the study and the implementation of the extension project and the operator is Hydro Exploitation SA. The FMHL power plant is a 240 MW pumped-storage power plant in Canton Vaud, Switzerland, which installed capacity is under extension to 480 MW with maximal output power set to 420 MW including 60 MW as reserve. This project, named FMHL+ consists in developing a new powerhouse to be operated in parallel to the existing powerhouse and connected to the same waterways. Increasing the output and input power of an existing hydroelectric scheme from 240 to 420 MW using existing head race tunnel and pressure shaft with maximum gross head of 878 mWC is a challenging task as far as the hydraulic transients are concerned.

This significant capacity increase required the modification of the hydraulic layout, by introducing a new vertical surge tank of 170 m high and 7.2 m of diameter, connected at the bottom to the existing headrace tunnel, and at the upper part to the already existing inclined surge tank, through a new connecting gallery. The new surge tank also includes a diaphragm in the connecting pipe to the headrace tunnel especially designed to improve the transient behaviour of the power plant in case of pump power failure. The surge tank design was performed by extensive transient simulations of the FMHL+ pumped-storage power plant using the simulation software SIMSEN and considering normal, exceptional and accidental load cases in turbine, pump and hydraulic short-circuit mode of operation.

The new surge tank has been successfully commissioned in November-December 2014 with the existing powerhouse (240 MW). The on-site hydraulic transient tests have been performed using a Real-Time Simulation Monitoring system (RTSM) enabling to compare in Real-Time, the simulation results of the FMHL pumped-storage power plant with the on-site measurements of relevant quantities such as surge tanks water levels, penstock pressure, headrace tunnel pressure and pump rotational speed. Indeed, the simulation being achieved with the detailed SIMSEN simulation model using measured boundary conditions corresponding to the reservoirs water levels and injector opening in turbine mode, it allows for a Real-Time comparison of simulation results with measurements with a direct and fast assessment of the hydraulic transient behaviour of the new layout.

The paper first presents the FMHL+ project and the challenges resulting from the significant power increase in turbine and pumping mode of operation and the technical solutions selected to accommodate this power increase. Then the paper presents the Real-Time Simulation Monitoring and the related power plant modelling used to perform the new surge tank commissioning. Finally comparison between simulation results and on-site measurements resulting from the Real-Time monitoring will be presented for the hydraulic transients tests of emergency shutdown in turbine mode at 60, 120, 180 and 240 MW and for emergency shutdown in pumping mode at -60 MW and -180 MW performed during the new surge tank commissioning in November-December 2014. Comparisons are also shown from tests performed in June-July 2016 with the new Unit 5 in case of 360 MW turbine emergency shutdown, -300 MW pump emergency shutdown as well as hydraulic short-circuit normal shutdown of new Unit 5. The good agreement between simulation results and measurements enabled to confirm the appropriate hydraulic transient behaviour of the new surge tank and its effectiveness in protecting the headrace tunnel against water hammer pressure waves.

1. FMHL+ Project

The increasing amount of new renewable energy sources (mainly solar and wind energy) in energy production in Europe requires also higher amounts of storage capacity and flexibility of the networks. One of the most efficient and cost effective methods of grid regulation and energy storage is still the use of pumped-storage plants. In order to be prepared for the future tasks, Forces Motrices Hongrin Léman SA (FMHL), decided to extend the capacity of the existing Hongrin-Léman pumped-storage scheme.

FMHL selected the GIHLEM consortium, constituted by Stucky, EDF-CIH and Emch-Berger engineering companies, to design the project, prepare the tender documents including the specifications and bidding procedure and moreover the execution design and the supervising of the final commissioning of the new power plant. The transient analysis was performed by GIHLEM consortium together with Power Vision Engineering Sàrl, as expert for the owner's representative.

The existing FMHL pumped-storage scheme, located in western Switzerland and commissioned in 1971, exploits a maximum head of 878 m between the upper Hongrin Reservoir (52 Mio m^3 at 1255 m a.s.l.) and Lake Geneva (89'000 Mio m^3 at 372 m a.s.l.) at the Veytaux I underground powerhouse. Figure 1 shows the general layout of the hydraulic system and the location of the production site at the Lake Geneva (also Léman Lake) near the city of Montreux.

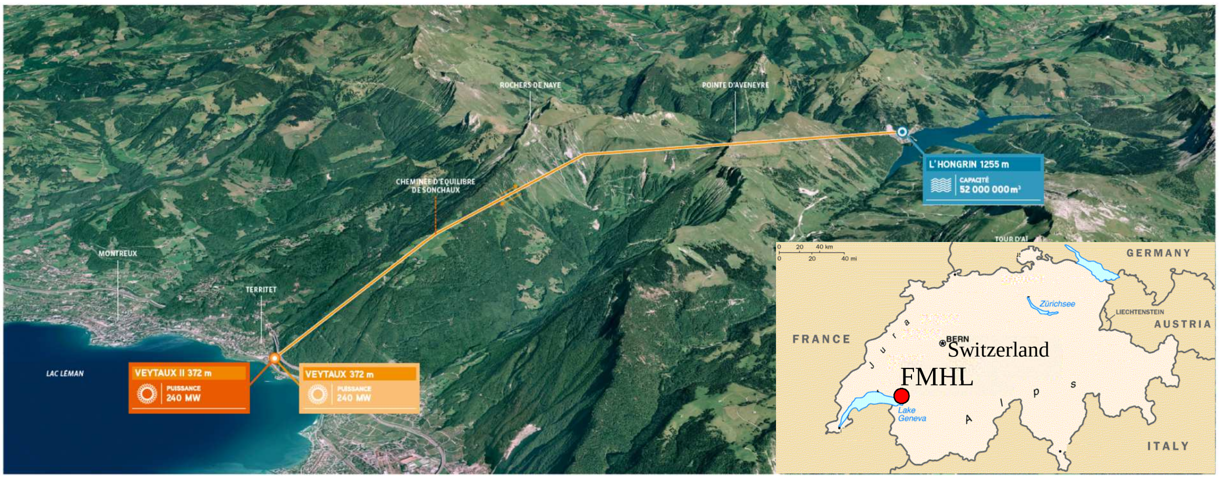


Figure 1. Location of the FMHL pumped-storage plant (right) and general layout (left) (red: new power station).

The objective of the FMHL+ enhancement project is to double today's plant capacity by building a new underground cavern adjacent to the existing one at Veytaux I. The new plant enables the production of regulation energy both in turbine and in pumping mode operating in hydraulic "short-circuit" mode. Two additional vertical ternary units of 120 MW each have been installed. The total power capacity will be 480 MW, with 420 MW as normal operating mode, and 60 MW as a reserve. The increased flexibility, generating peak electricity, will allow the plant to play a key role in supplying electricity to western Switzerland and meeting the growing demand for balancing energy.

The power extension was made possible in FMHL+ project, first by choosing ternary units with Pelton turbine and multistage pumps (with 5 impellers per unit), leading to better transient results than the solution of double stage regulated reversible pump-turbines, then by modifying the existing surge tank.

2. Presentation of Hongrin-Léman Power Plant

2.1. General description

Figure 2 presents the profile of the FMHL pumped-storage power plant, comprising the Hongrin double arch dam leading to the Hongrin reservoir with maximum water level of 1255 masl, a 8 km long headrace tunnel with a maximum diameter of 4 m, the surge tank of Sonchaux featuring upper and lower expansion chambers, a 1.2 km long pressure shaft, the Veytaux I underground powerhouse with installed capacity of 240 MW connected downstream to the Léman Lake with minimum water level of 371 masl. The new Veytaux II underground powerhouse is located next to the existing one with an installed capacity of 240 MW, see Figure 3, and is connected to the existing pressure shaft. The two powerhouses are equipped with ternary units with Pelton turbines, synchronous motor-generators, and multistage pumps with respectively horizontal and vertical orientation of rotational axis. The main characteristics of the electromechanical equipment are summarised in Table 1, and the cross section views of the existing and new units are presented in Figure 4 and Figure 5 respectively. Detailed description of the FMHL+ extension project and ongoing works can be found in ref [7], [8] and a detailed description of the new electromechanical equipment is provided in ref [4]. The new multistage pumps of Veytaux II are provided by VOITH Hydro, see ref [6], while the new synchronous motor-generator and the new Pelton turbines are provided by ANDRITZ Hydro, see Figure 6. The valves are provided by the consortium ANDRITZ Hydro / D2FC.

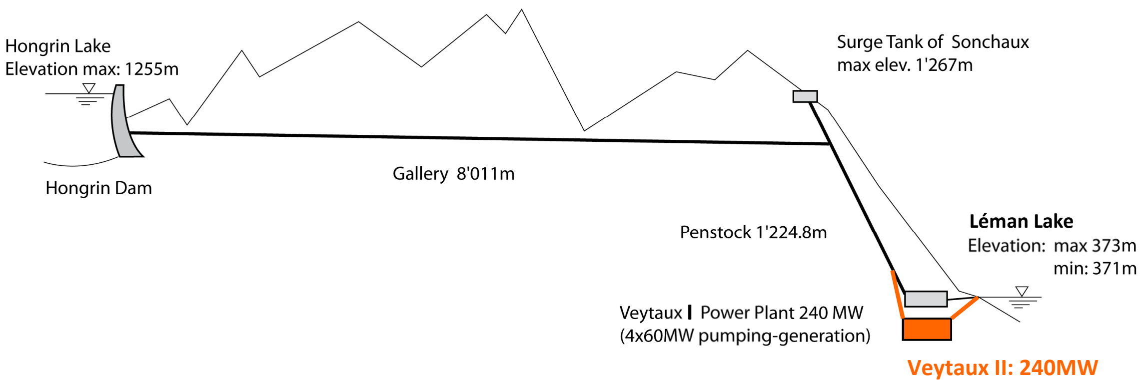


Figure 2. Layout of the FMHL power plant with existing Veytaux I powerhouse with 240 MW total capacity and the Veytaux II powerhouse with additional 240 MW.

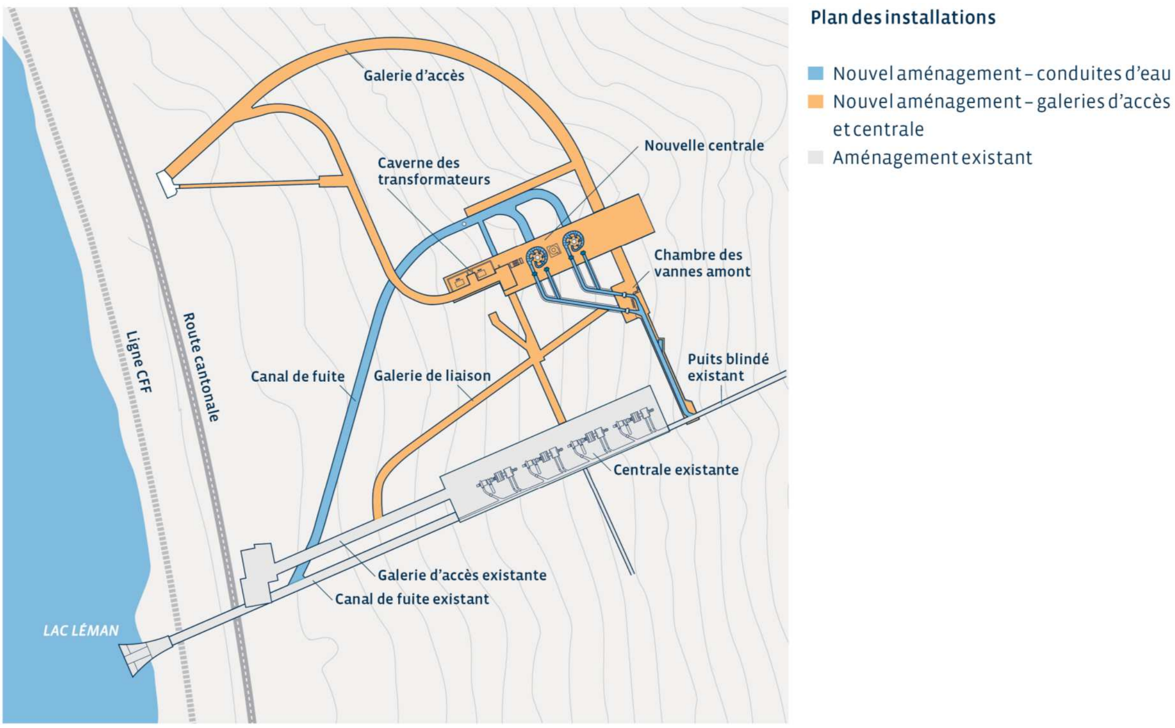


Figure 3. Top view of the existing (gray) and new (colourful) powerhouses Veytaux I and Veytaux II, [4].

Table 1. Characteristics of the electromechanical equipments of Veytaux I and Veytaux II powerhouse.

	Veytaux I		**Veytaux II**	
	Generation	Pumping	Generation	Pumping
Total rated capacity	240 MW		240 MW	
Number of units	4		2	
Axis orientation	Horizontal		Vertical	
Rotational speed	600 rpm		500 rpm	
Nominal discharge	32.5 m^3/s	24 m^3/s	32 m^3/s	24.6 m^3/s
Maximum gross head	878mWC	884mWC	879mWC	884mWC
Number of runners / Impellers per unit	2	5	1	5
Number of injectors per runner	2	-	5	-
Feeding pump	-	Yes	-	No
Coupling of the pump	Mechanical coupling with Pelton runner for synchronization in air		Mechanical coupling at standstill (space reserved for hydraulic torque converter for a possible future integration)	

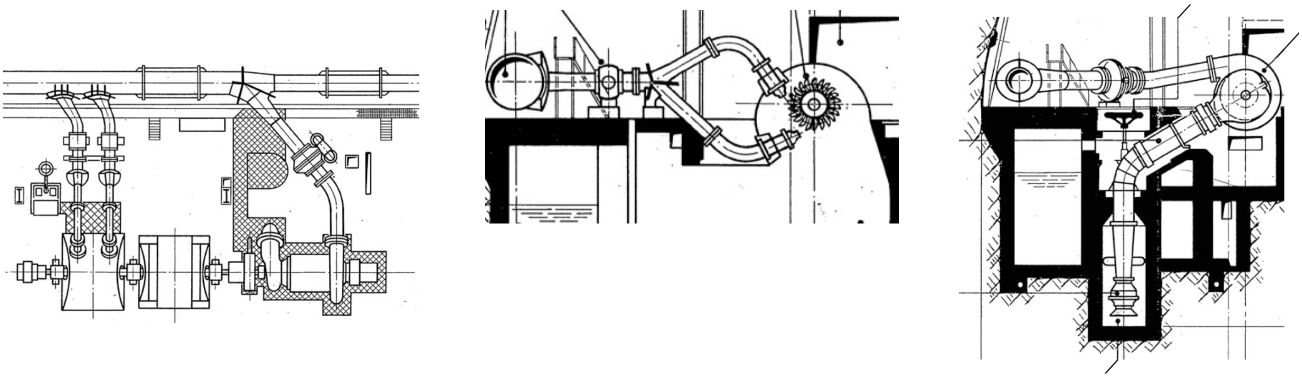


Figure 4. Top view of one Unit arrangement (left) and cross section view of the turbine (middle) and of the pump (right) of Veytaux I Powerhouse, source FMHL.

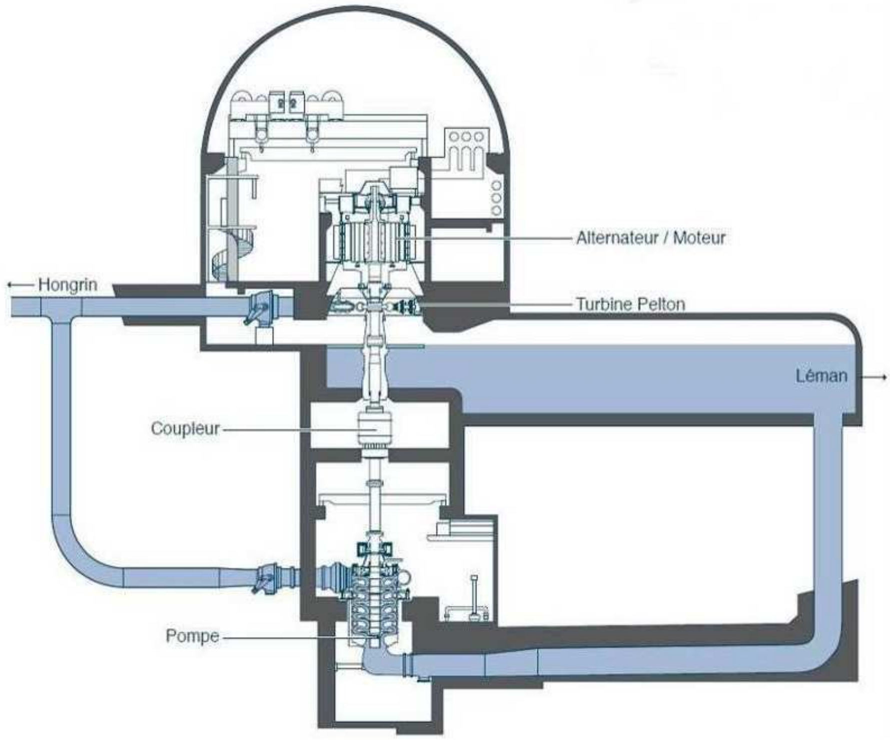


Figure 5. Cross section view of the ternary Unit of Veytaux II Powerhouse, [4].

Figure 6. Pictures of the new unit 5 of Veytaux II including 5 stages storage pump (left) and Pelton turbine with 5 injectors (right), [8].

2.2. New surge tank to accommodate power extension

Among the expected risks resulting from capacity increase [11], [15], [18], [19], for FMHL+ the most problematic case was found to be related to the pump power failure at -420 MW and the related risk of low pressure in the headrace tunnel. Indeed, the increase of discharge in pumping mode lead to a very fast water level drop in the surge tank in case of pump power failure. Moreover, this fast water level drop comes along with a fast drop of pressure in the headrace tunnel, while the headrace profile presents a slope discontinuity after a flat zone at around 80% of its length, that increases the risk of water column separation.

Figure 7 left presents the minimum and maximum piezometric envelopes obtained in the headrace tunnel from the simulation of the emergency shutdown in pumping mode at -420 MW for the target minimum water level without any modification of the surge tank. The minimum piezometric envelopes evidences pressures below atmospheric pressure over more than 80% of the headrace tunnel and negative pressure that would lead to water column separation over about 30% of the headrace tunnel. Such situation would of course not being acceptable, and thus required surge tank modification and optimisation. Besides low pressure risk in the gallery, the surge tank modification was also necessary with respect to the maximum water level.

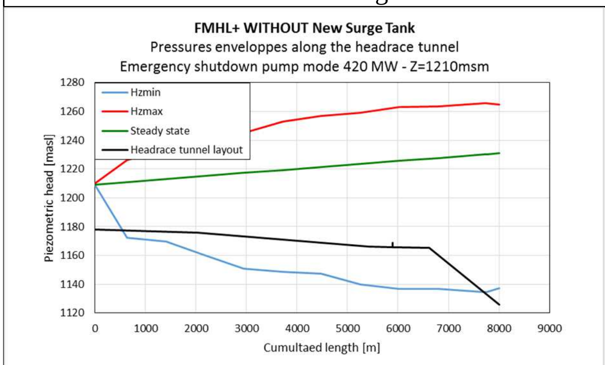
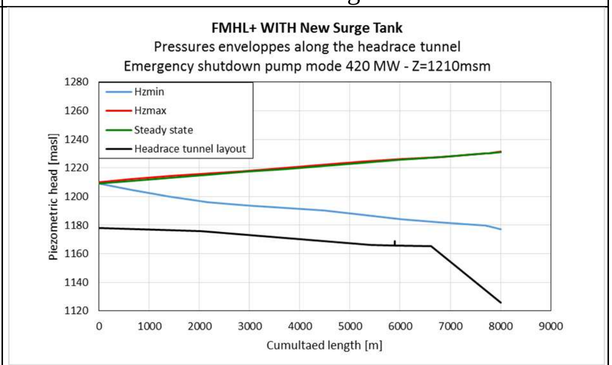
WITHOUT New Surge Tank	WITH New Surge Tank
	

Figure 7. Minimum and maximum piezometric head envelopes in the headrace tunnel obtained with (left) or without (right) the new surge tank in case of emergency shutdown in pumping mode at 420MW and Z=1210 masl.

Figure 8 presents the surge tank in final configuration, which consists of a new vertical surge shaft of 7.2 m of diameter and a height of 170 m, connected directly in its lower part to the headrace tunnel via a connecting pipe where a diaphragm has been installed, see Figure 9, while the existing inclined surge tank was modified by by-passing the upper expansion chamber to connect directly to the new vertical surge shaft at the top. Special care has been paid to optimise the diaphragm head losses for the pumping mode of operation to mitigate the low pressure in the headrace tunnel. The optimisation was performed using a SIMSEN simulation model, see Figure 13, taking into account Veytaux I and II power plants and the new surge tank configuration, and simulating two different load cases: 1) the emergency shutdown at -420 MW in pumping mode at lowest Hongrin water level, and 2) the same case assuming that the pump discharge valve of one the new pumps fails to close, see [11]. Figure 10 presents the comparison of the simulation results obtained with and without surge tank modification for the time evolution of the original surge tank water level and for the headrace tunnel piezometric head at the slope change point (x=~6790m) in case of pump power failure at 420 MW and minimum expected water level 1210 masl. The resulting pressure envelopes are presented in Figure 7. It could be noticed that the new surge tank completely changes the dynamic behaviour of the headrace tunnel-surge tank system. Indeed, as expected the new surge tank enables to: (i) reduce water level oscillation amplitude in the surge tank, (ii) drastically reduce pressure fluctuations in the headrace tunnel, (iii) and provides significant additional damping of the surge tank mass oscillations.

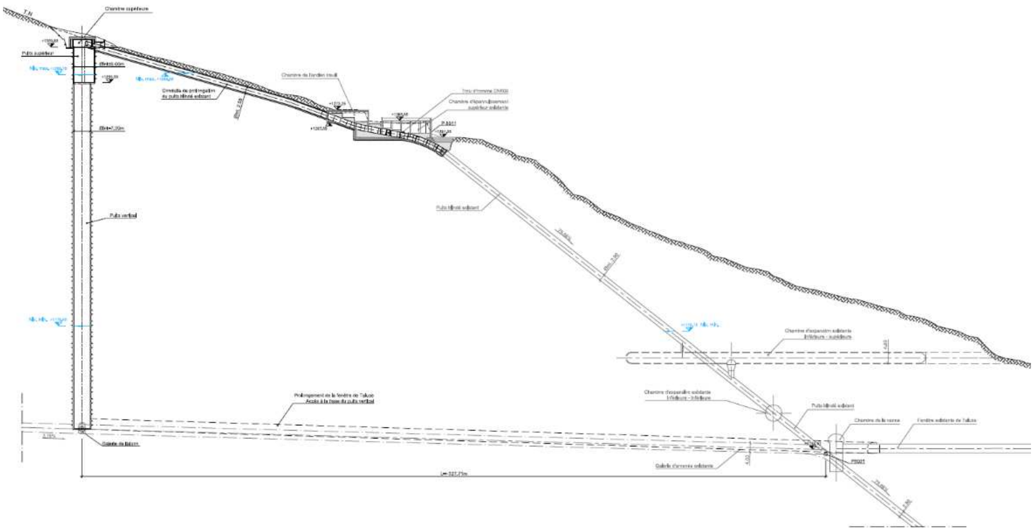


Figure 8. New surge tank cross section view.

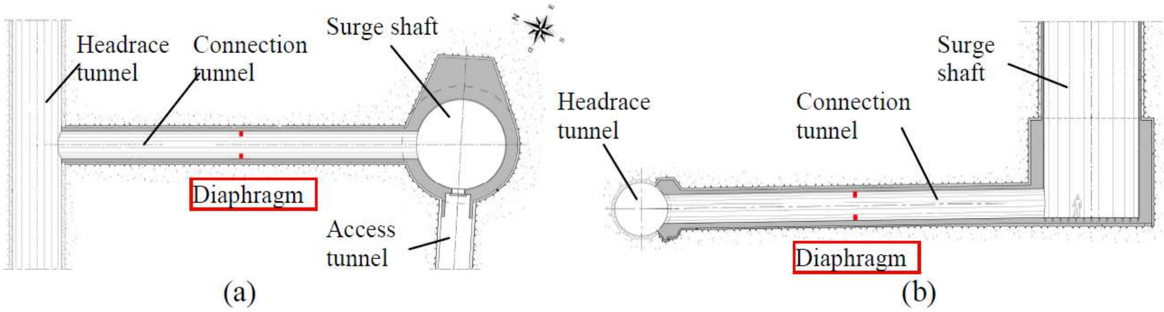


Figure 9. The new surge shaft and the connection and headrace tunnels; (a) Plan view; (b) Longitudinal section. The diaphragm inside the connection tunnel is also shown, [3].

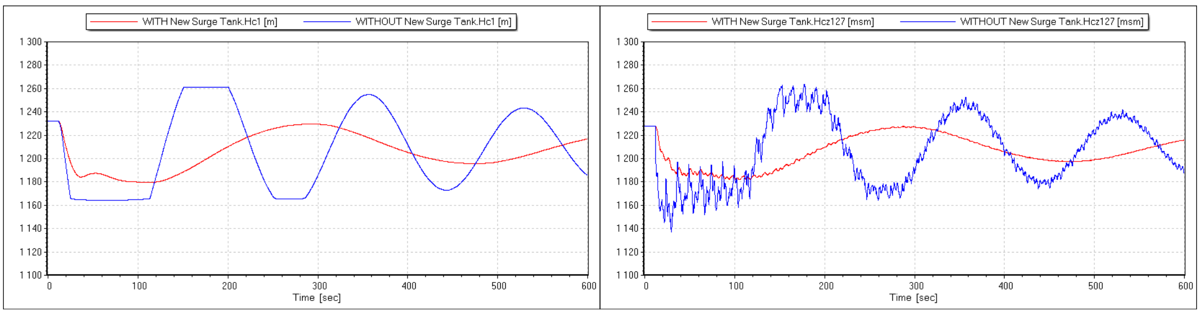


Figure 10. Comparison of simulation results of the time evolution of the original surge tank water level (left) and of the piezometric head in the headrace tunnel at the slope change location (x=6790m) obtained with or without the new surge tank in case of emergency shutdown in pumping mode at -420MW and Z=1210 masl.

Once the diaphragm head losses were optimised from the hydraulic point of view, physical model tests of the surge tank have been carried out at the EPFL Laboratory of Hydraulic Constructions to determine the geometry of the diaphragm, see [3], and to determine the related head losses for various flow configurations. The increase of the maximum water level in this surge shaft induced by the power increase has also been considered to design the surge shaft, see [6], [11].

3. Hydro-Clone Real-Time Simulation Monitoring System

3.1. General description

The Hydro-Clone is an innovative Real-Time Simulation Monitoring System (RTSM) comprising a well calibrated and validated digital clone 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 [12], [2]. This system [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 [9], [16] and existing key monitoring points. As illustrated in Figure 11, 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.

As illustrated in Figure 12, 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;
- 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.

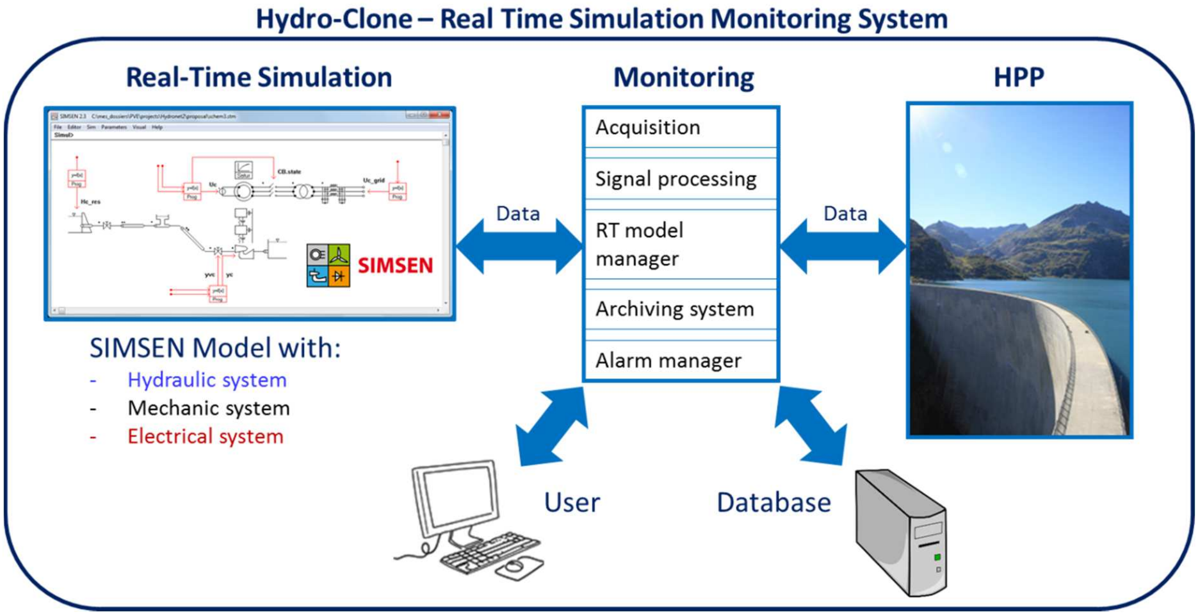


Figure 11. General concept of Hydro-Clone based on Real-Time Simulation of HPP.

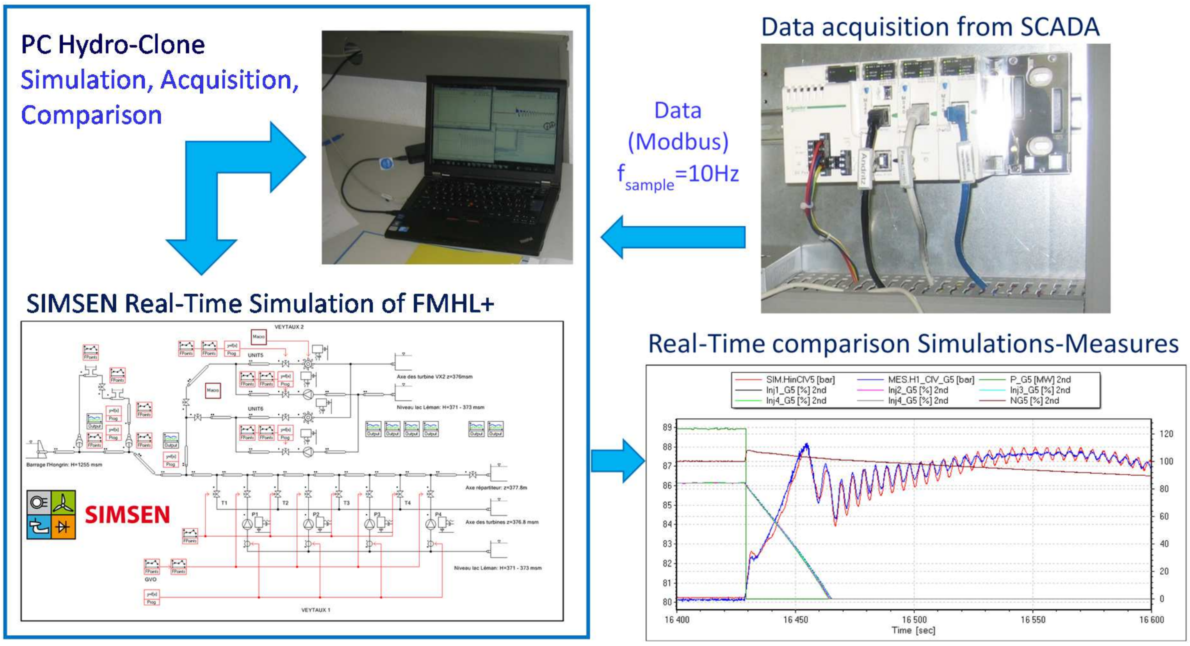


Figure 12. Hydro-Clone as used for the commissioning of Veytaux II new 120 MW units.

3.2. Application of Hydro-Clone for FMHL+ hydraulic transients tests

The Hydro-Clone Real-Time Simulation Monitoring system was used during the hydraulic transient tests of the FMHL+ project. First, for the commissioning of the new surge tank in November-December 2014, and then for the commissioning of the 2 new units in June to October 2016, to confirm that the transient behaviour of the extended pumped storage plant corresponds to the expected behaviour. The main motivation of using the Real-Time Simulation Monitoring system during the commissioning phases of FMHL+ project are:

- Direct access to real-time comparison between simulation results and on-site measurements;
- On-line assessments of power plant hydraulic transient behaviour conformity with simulation model used during the design and verification phases;
- Fast discrepancies identification and root cause diagnosis in case of differences between simulation results and measurements;
- Significant reduction of the time required for the transient behaviour conformity verifications and decision process to allow next transient test.

Figure 13 presents the SIMSEN simulation model of the Hongrin-Léman pumped storage plant corresponding to the final configuration after commissioning of the new surge tank as well as the two new units of 120 MW each. This simulation model was used together with the Hydro-Clone system to perform Real-Time simulations during the hydraulic transient tests in order assess in real-time the conformity of the transient behaviour of the new equipment with the expected behaviour. The SIMSEN model of Figure 13 includes:

- The upper reservoir with constant water level;
- The pressurized headrace tunnel;
- The new vertical surge tank with its diaphragm in the linking gallery to the headrace tunnel, see[3], [11];
- The existing inclined surge tank taking into account the connection to the new vertical surge tank in the upper part, the inertia of the water of the inclined shaft which affects considerably the transients pressures in the headrace tunnel, see [13], and the head losses of the junction to the headrace tunnel;
- The existing 1200 m long inclined pressure shaft;
- The manifold distributing/collecting the water between the 4 units of the existing Veytaux I power plant and the 2 units of the Veytaux II power plants;
- The 4 ternary units of Veytaux I with 60 MW Pelton turbine and 60 MW multi-stage storage centrifugal pump each taking into account the feeding pumps;
- The 2 ternary units of Veytaux II with 120 MW Pelton turbine and 120 MW multi-stage storage centrifugal pump enabling hydraulic short-circuit operation;
- The main inlet valves of the turbines (MIV), the pump discharge valves (PDV), the common inlet valve of the units (CIV).

The multi-stages pumps are modelled with their 4 quadrants characteristics and the inertia of the rotating mechanical masses (pump, Pelton turbine, coupling shafts and motor-generator). The Pelton turbine of the 2 units are modelled with 2 quadrants characteristics taking into account the deflectors as well as the link to mechanical rotating inertia and enabling to simulate individual injector manoeuvers. The hydraulic short-circuit operation of the units can be simulated as the model of the units includes the detailed model for the storage pump and Pelton turbine transient behaviour and the related mechanical coupling. The model does not include the dynamic behaviour of the electrical system.

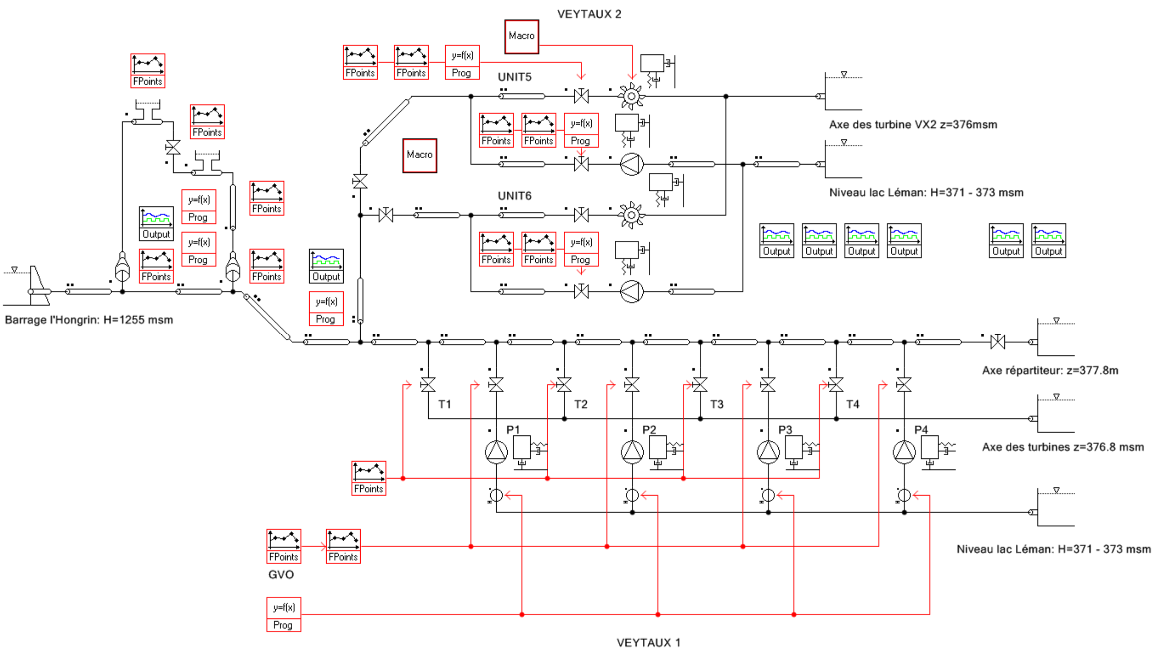


Figure 13. SIMSEN model of FMHL+ pumped storage plant.

It could be mentioned that the SIMSEN simulation model of the original configuration of FMHL was dully validated based on available measurements performed before the power extension. Then the SIMSEN model was extended to the FMHL+ configuration including the new 120 MW Units 5 and 6 based on data provided by the equipment suppliers and including the new surge tank based on its geometry and the results of the reduced scale physical tests performed for the diaphragm design.

4. Results of commissioning campaigns

The Hydro-Clone Real-Time Simulation Monitoring system has been used during hydraulic transient tests performed for commissioning of the new surge tank with a total power of 240 MW in November-December 2014, as well as for the commissioning of the new 120 MW Unit 5 in June-July 2016 to compare in Real-Time simulation results with on-site measurements. The comparison between simulation results and measurements performed during these two hydraulic transient test campaign are presented in the following subchapters.

4.1. Commissioning of the new surge tank November-December 2014

To confirm the correct transient response of the new FMHL+ surge tank, transient tests have been performed first in turbine mode in case of emergency shutdown (ESD) stepwise for different initial power levels from 60 MW to 240 MW with only Veytaux I in operation when the new surge tank was connected to the existing headrace tunnel in November-December 2014. The comparison between Real-Time simulation results and on-site measurements of the time evolution of the new surge tank water level as well as of the pressure shaft pressure are presented in Figure 14. The simulations have been performed by imposing upstream water level and measured position of the Pelton turbine injectors in Real-Time obtained from the SCADA system via Ethernet.

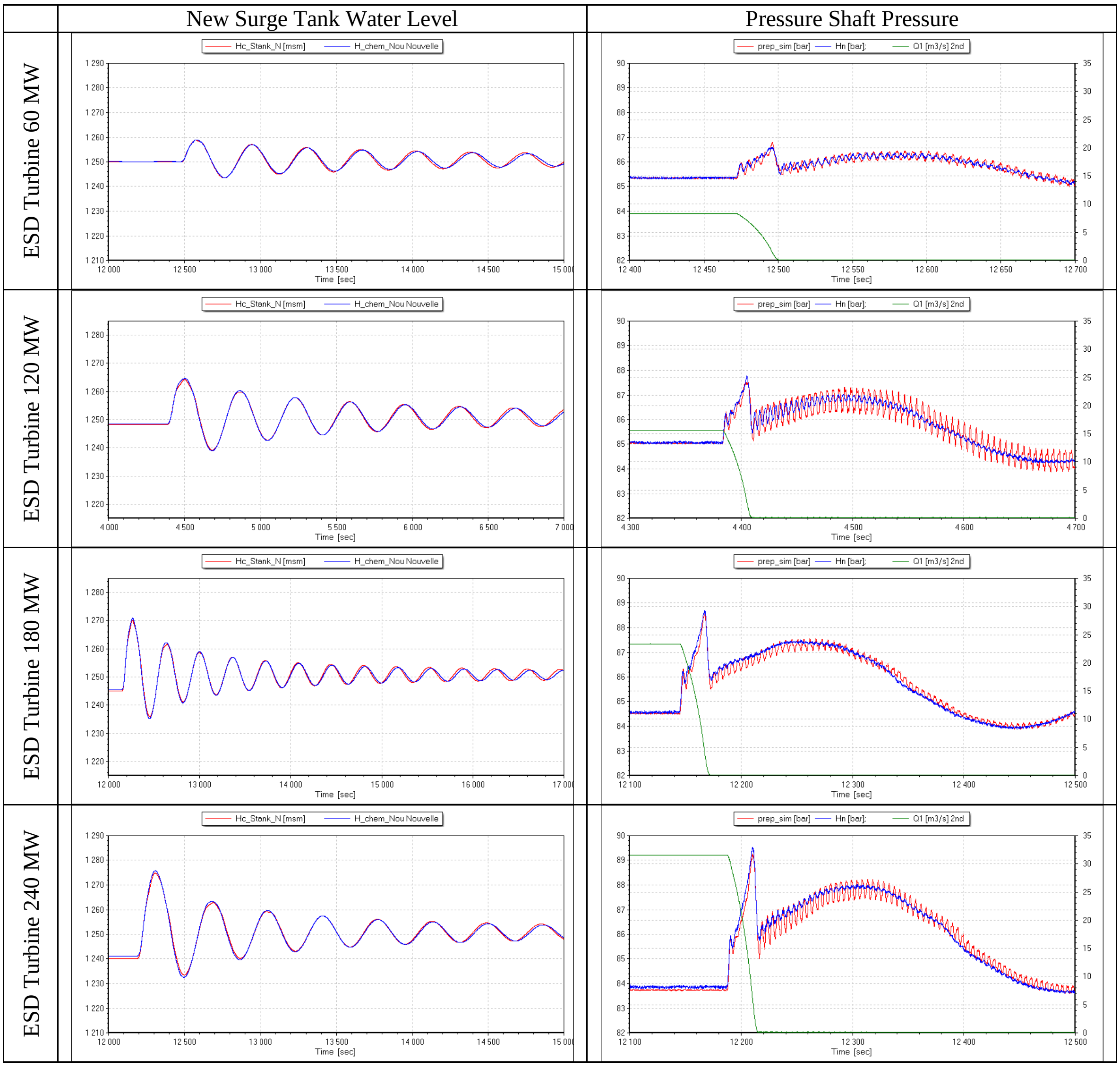


Figure 14. Comparison between Real-Time simulation results (red) and on-site measurements (blue) obtained during hydraulic transient tests performed for the commissioning of the new FMHL+ surge tank in November-December 2014 in case of turbine emergency shutdown (ESD) for different initial power levels.

The simulation results obtained without additional calibration of the model during the transient test show very good agreement with the on-site measurements in terms of maximum amplitudes of pressure and surge tank water levels, period and damping of the surge tanks mass oscillations. The Real-Time simulations enabled very fast comparison between simulations and measurements and allowing for performing next transient test with increased power level in a safe and confident conditions within reduced time.

Based on the good agreement obtained in turbine mode with the new surge tank, then hydraulic transient tests have been carried out in pumping mode with only Veytaux I in operation. The comparison between Real-Time simulation results and on-site measurements are presented in Figure 15 for the time evolution of the pressure shaft pressure, new surge tank water level, head race tunnel pressure measured close to the original surge tank and for the pump rotational speed, in case emergency shutdown of 1 and 3 units of Veytaux I operating in pumping mode respectively at -60 MW and -180 MW.

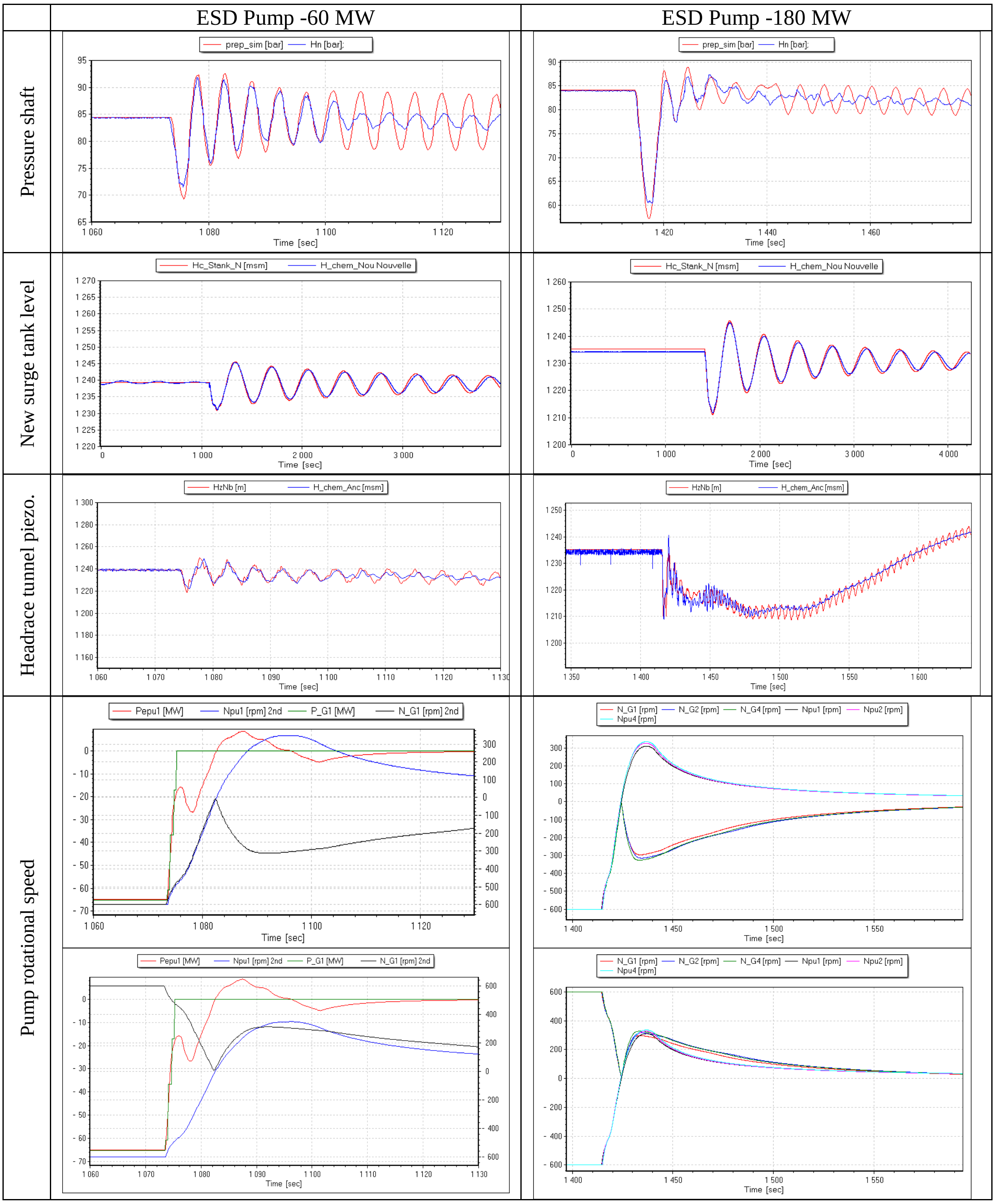


Figure 15. Comparison between Real-Time simulation results (red) and on-site measurements (blue) obtained during hydraulic transient tests performed for the commissioning of the new FMHL+ surge tank in November-December 2014 in case of pump emergency shutdown (ESD) for different initial power levels.

The comparison between Real-Time simulation results and on-site measurements presents, also in pump mode, very good agreements. Particular attention was paid in pump mode for the comparison of the pressure in the headrace tunnel close to the original surge tank. The very good agreement obtained for this pressure confirms the appropriate modelling of the new and the original surge tanks, and thus correct prediction of pressure in the whole headrace tunnel are also expected. Good accuracy for the diaphragm head losses resulting from physical model tests and the consideration of the original surge tank water inertia appeared to be decisive to reach good agreement between simulation results and on-site measurements. Finally, some differences of the pressure shaft pressure could be noticed in case of pump ESD after the closure of the pump discharge valve (PDV). This difference is due to the fact that the closure of the PDV seal was not taken into account in the numerical simulation.

4.2. Commissioning of new Unit 5 in June 2016

Hydraulic transient tests were carried out during the commissioning of the new Unit 5 in June 2016. These tests benefited from the validation of the new surge tank performed with 240 MW during the hydraulic transient test at the end of 2014. First hydraulic transient tests were performed with the new Unit 5 in turbine mode alone for different power levels, not presented here. Based on the good agreement obtained for the Unit 5 alone transient test have been performed stepwise until 360 MW in turbine mode. Same approach was used to perform the hydraulic transient tests in pump mode after the validations obtained in turbine mode. Figure 16 presents the comparison between Real-Time simulation results and on-site measurements in case of Emergency Shutdown in turbine mode at 360 MW with 5 units in operation and in pump mode at -300 MW with 4 units in operation.

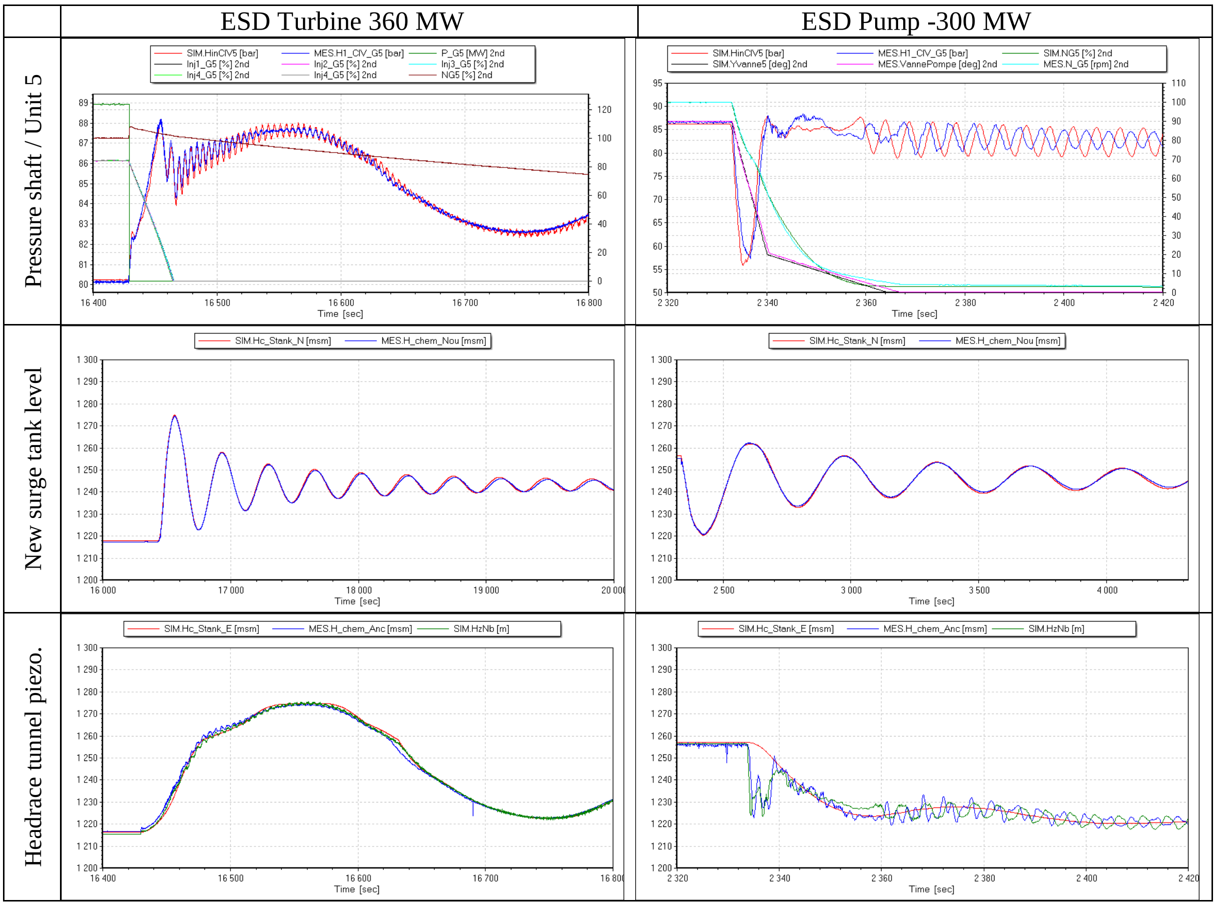


Figure 16. Comparison between Real-Time simulation results (red) and on-site measurements (blue) obtained during hydraulic transient tests performed for the commissioning of the new unit 5 in June 2016 in case of turbine and pump emergency shutdown (ESD) for different initial power levels.

In general good results were obtained in turbine mode while some extra calibrations of the SIMSEN model were needed for the simulations performed in pump mode. Indeed, the pump discharge valve (PDV) of the new unit appeared to feature higher head losses than originally foreseen. These additional head losses lead to an improved transient behaviour of the units in pump mode, as for the same PDV closing law, the rotational speed reduction was slower. Calibration was performed after the first ESD test in pump mode and extensive simulations were performed to confirm the appropriate transient behaviour in pumping mode with the updated PDV head loss characteristics prior to perform additional transient tests. The comparison presented in Figure 16 have been obtained with the calibrated PDV head loss characteristics. Very good agreement have been obtained between simulations and on-site measurements for the time evolution of the pressure shaft pressure, and for the new surge tank water level evolution. After calibration of the PDV head losses, very good agreement of the unit 5 rotational speed was reached in pump mode. As mentioned in the previous subchapter, the very good agreement of the pressure in the headrace tunnel was again an important step to confirm the new surge tank effectiveness in protecting the headrace tunnel against the low pressure induced tripping of the units in pump mode.

4.3. Optimisation of Unit 5 hydraulic short-circuit normal shutdown sequence in July 2016

The normal shutdown sequence of the ternary Unit 5 was optimised in case of operation in hydraulic-short-circuit. During hydraulic short-circuit, the pump is in normal operation and the Pelton turbines controls the active input power of the unit. At the end of a hydraulic short-circuit sequence, normal shutdown of the unit involves the closure of the turbine injectors and the pump discharge valve as well as the opening of the circuit breaker. At least 3 aspects have to be taken into consideration during the normal shutdown optimisation process: (i) the maximum pressure induced in the pressure shaft, (ii) the value of the apparent power, and thus of the current, through the circuit-breaker at the moment of its opening, and (iii) the time to reduce the rotational speed from nominal speed down to zero. Figure 17 presents the comparison between off-line simulation and on-site measurement of the original normal shutdown sequence in hydraulic short-circuit. As it could be seen, very good agreement is achieved between numerical simulation results and measurements enabling the sequence optimisation. This first sequence was based on the normal pump shutdown combined with initial active power set point of -30 MW in order to minimize the apparent power through the circuit breaker at the time of its opening. It could be noticed that significant overpressure occurs after the PDV closure law slope change (t=~6815s) and also that the rotational speed experiences a stabilisation close to nominal speed after the circuit breaker opening (t=~6812 to 6820s).

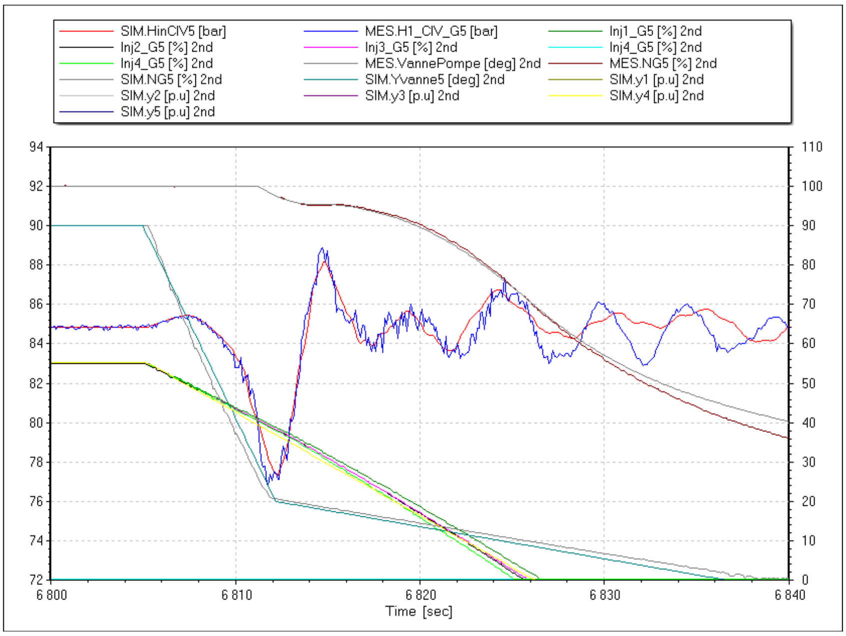


Figure 17. Comparison between simulation results (red) and on-site measurements (blue) obtained from hydraulic transient tests performed of the new unit 5 in July 2016 in case of normal shutdown performed in hydraulic short-circuit at -30 MW with 4 injectors.

Numerical simulations have been performed to optimise this sequence, and a first compromise was found by reducing the initial active input power to -60 MW at the moment of the circuit breaker opening and to keep 5 injectors in operation. The comparison of off-line simulations and on-site measurements of the resulting sequence is presented in Figure 18. As expected, the overpressure following the PDV closing slope modification was significantly reduced and the rotational speed slow down faster as the injectors closure time are shorter than for the original sequence. Finally, additional simulations were performed to further optimise this sequence in terms of overpressure, and the time evolution of the pressure shaft pressure and the corresponding unit rotational speed obtained for different combinations of initial active power and number of injectors in operation is presented in Figure 19. The final sequence corresponds to an initial active power of -60 MW but operation with 4 injectors (see green curves). This sequence enables to reduce the first pressure peak at the beginning of the sequence, and keep a fast slowdown of the rotational speed of the unit while the initial active input power of the unit is set to -60 MW, corresponding to half of the power of the unit.

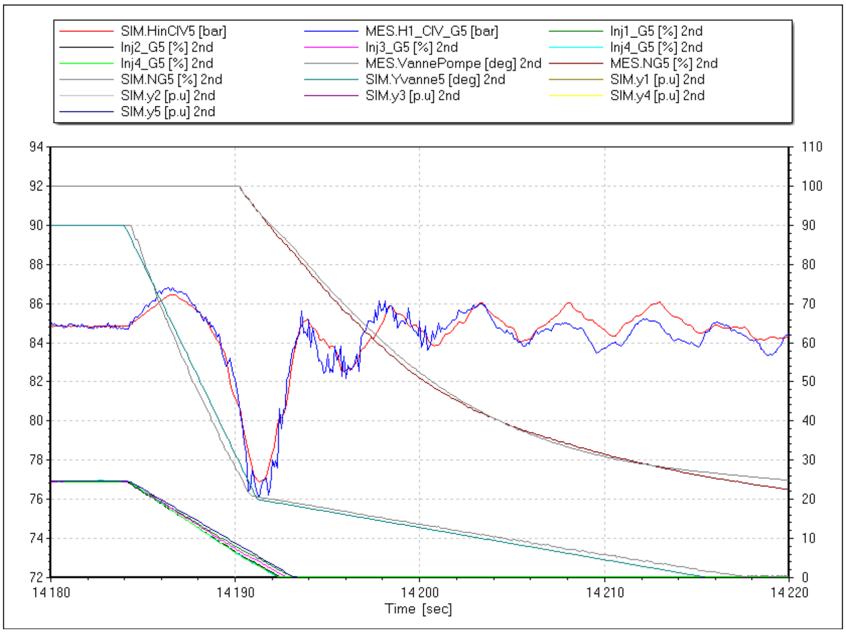


Figure 18. Comparison between simulation results (red) and on-site measurements (blue) obtained from hydraulic transient tests performed of the new unit 5 in July 2016 in case of normal shutdown performed in hydraulic short-circuit at -60 MW with 5 injectors.

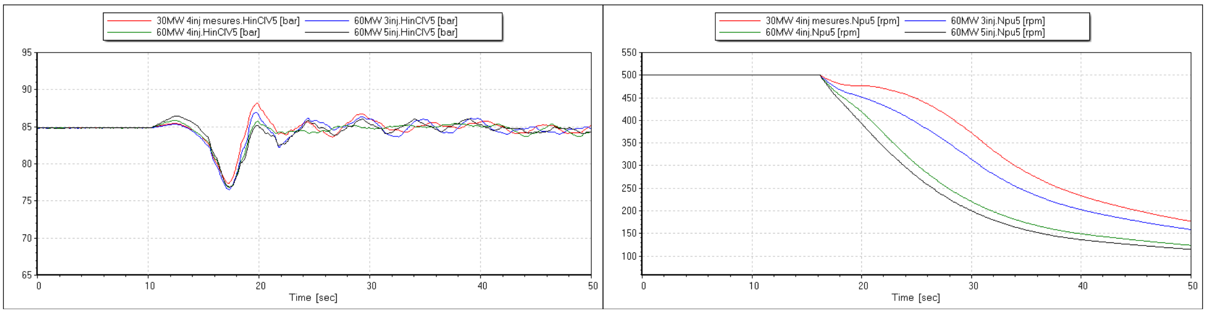


Figure 19. Comparison between simulation results of the pressure shaft pressure (left) and of the unit rotational speed (right) obtained for the new unit 5 in case of normal shutdown performed in hydraulic short-circuit for different power and injectors configurations.

5. Conclusions

The increase of the total capacity of the FMHL pumped-storage power plant from 240 to 420 MW under realisation within the FMHL+ project is a challenging task as far as the hydraulic transients are concerned. Thanks to the selection of the ternary units arrangement for the units of the new Veytaux II powerhouse, the maximum pressure in the pressure shaft can be kept to the same maximum value resulting from the operation of the original Veytaux I powerhouse with FMHL power plant. The maximum pressure is set to 109% of the maximum static head, while the pressure shaft was designed for 115%, see [8]. Then, the most critical point to accommodate the hydraulic transients resulting from the significant power increase was found to be related to the minimum pressure in the headrace tunnel in case of emergency shutdown in pumping mode at -420 MW. Indeed, the simulation in pumping mode with the original surge tank have shown pressure below atmospheric pressure over more than 80% of the total length of the headrace tunnel and a risk of water column separation over more than 30% of the total length of the headrace tunnel. To solve this low pressure issue, a new vertical surge tank was designed by iterative numerical simulation process taking into account several load cases in pump, turbine and hydraulic short-circuit operation. Once the surge tank was hydraulically designed, physical model tests have been undertaken to define the appropriate geometry of the diaphragm of the surge tank which was specifically optimised for the pumping mode operation, see [11] , [3].

The commissioning of this new surge tank in November-December 2014 was an important step for the FMHL+ project and required particular attention. Therefore, the project team took advantage of the Hydro-Clone Real-Time Simulation Monitoring system in order to assess in Real-Time the hydraulic transient behaviour of the power plant during the commissioning of the new surge tank and thus guaranty the equipment and personal safety. The on-site tests performed stepwise, first in turbine mode then in pump mode have shown a very good agreement between Real-Time numerical simulations results and on-site measurements and thus confirmed the new surge tank effectiveness in protecting the headrace tunnel against low pressures. This was made possible thanks to the power plant Owner's representative commitment in the project design process. Indeed, many actions have been undertaken to minimize uncertainty of the numerical simulations, such as on-site tests that have been carried out during FMHL+ design process to allow for thorough validation of the SIMSEN simulation detailed model of the FMHL pumped storage power plant in its original configuration, or physical model tests of the new surge tank performed to guaranty the new diaphragm design.

The hydraulic transient tests carried out during the commissioning of the new 120 MW Unit 5 in June 2016 further confirmed the appropriate transient response of the new surge tank with transient tests performed at 360 MW in turbine mode and -300 MW in pumping mode. Very good agreement was also obtained between Real-Time simulations and on-site measurements. The next step will be the transient tests at 420 MW to be carried out in September-October 2016 with the commissioning of the new 120 MW Unit 6.

The use of Real-Time Simulation Monitoring system during the commissioning phase of the new surge tank in 2014 and then during the commissioning of the new units in 2016 appeared to be an efficient way to assess hydraulic transients and thus guaranty the safety of the power plant during the hydraulic transient tests. Besides the advantages of direct comparison between simulation results obtained with the simulation model used during the design phase and the on-site measurements, the Real-Time Simulation Monitoring also revealed to be a way to reduce the commission time thanks to reduced time of the decision process after each tests. Moreover, the system also enabled to perform off-line simulations in parallel of the ongoing transient tests to optimise the normal operation sequences such as the hydraulic short-circuit normal shutdown sequence, which also benefited from the presence of all experts involved in the decision process during the commissioning.

The new Veyatux II powerhouse should be fully in operation by the end of the year. With +420 MW to -420 MW power output/input capacity and increased flexibility gained thanks from hydraulic short-circuit, the newly upgraded FMHL+ pumped storage plant will represent a major asset to contribute to power network stability in a constantly changing electricity market.

6. Acknowledgements

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7. Nomenclature

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

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8. 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 20, yields to the following set of hyperbolic partial differential equations [20]:

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

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 [5], [14], [17] as presented in Figure 21. The RLC parameters of this equivalent scheme are given by:

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

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 21. 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, [9], [10]. The time domain integration of the full system is achieved in SIMSEN by a Runge-Kutta 4th order procedure.

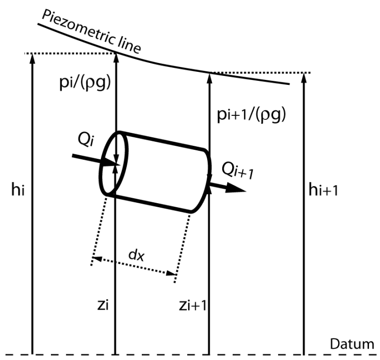

Figure 20 Elementary hydraulic pipe of length dx.

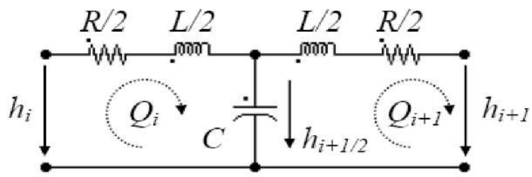

Figure 21 Equivalent circuit of an elementary pipe of length dx.

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 [9]. 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:

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