Hydraulic transient challenges for the upgrade of FMHL+ pumped storage power plant from 240MW to 420MW

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Abstract. The FMHL power plant was originally a 240 MW pumped-storage power plant in Canton Vaud, Switzerland, which installed capacity was recently extended 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 headrace tunnel and pressure shaft with maximum gross head of 878 mWC is a challenging task as far as the hydraulic transients are concerned. 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 transient tests. 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 428 MW and for emergency shutdown in pumping mode at -420 MW performed. The good agreement between simulation results and measurements enabled to confirm the appropriate hydraulic transient behavior of the new surge tank and its effectiveness in protecting the headrace tunnel against water hammer pressure waves.

1. Introduction

The FMHL (Forces Motrices Hongrin-Léman SA) company 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 FMHL+ and the operator is Hydro Exploitation SA. The FMHL power plant was originally a 240 MW pumped-storage power plant in Canton Vaud, Switzerland, which installed capacity was recently extended 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 headrace 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 surge tank design was performed by extensive transient simulations of the FMHL+ pumped-storage power plant considering normal, exceptional and accidental load cases in turbine, pump and hydraulic short-circuit mode of operation. The new power house has been successfully commissioned in 2016 and is in normal operation since January 2017. 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.

2. Presentation of Hongrin Léman pumped storage power plant

2.1. General presentation

The profile of the FMHL pumped-storage power plant, see Figure 1, is 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, 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 cross section views of the existing and new units are presented in Figure 2 and Figure 3 respectively, while the main characteristics of the electromechanical equipment are summarised in Table 1. Detailed description of the FMHL+ extension project and ongoing works can be found in [7], [8] and a detailed description of the new electromechanical equipment is provided in [4], [6].

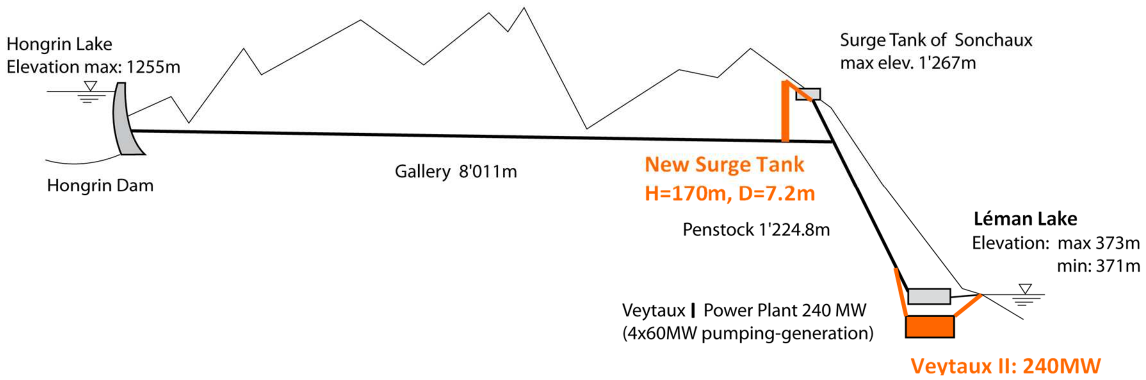

Figure 1. Layout of the FMHL power plant with existing Veytaux I powerhouse with 240 MW total capacity and the Veytaux II powerhouse with additional 240 MW.

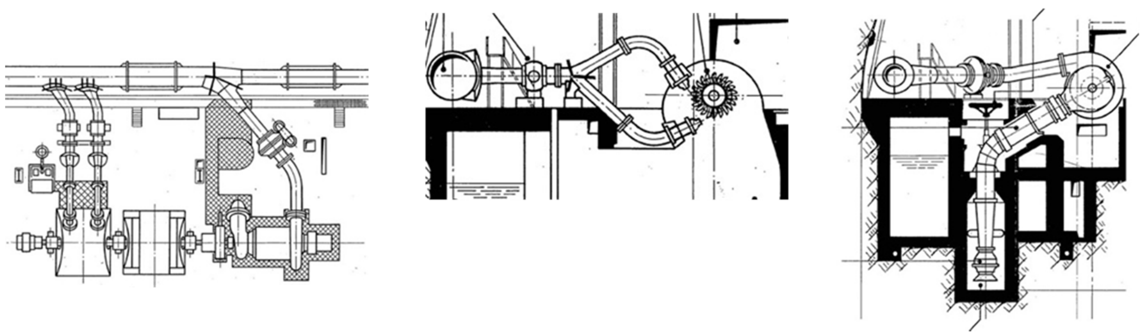

Figure 2. Top view of one Unit arrangement (left) and cross section view of the turbine (middle) and of the pump (right) of Veytaux I Powerhouse, source FMHL.

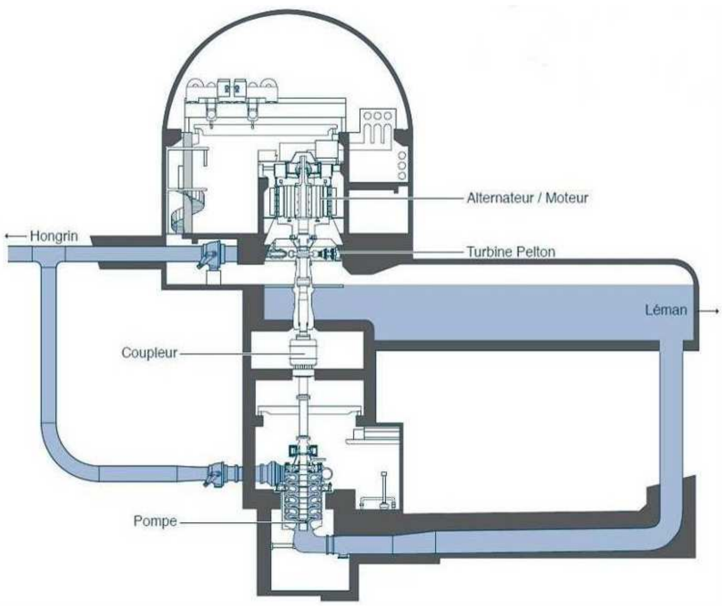

Figure 3. Cross section view of the ternary Unit of Veytaux II Powerhouse.

Table 1. Characteristics of the electromechanical equipment 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)	

2.2. New surge tank design

Among the expected risks resulting from capacity increase [5], [11], [15], [17], [18] 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 4 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 5, 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, 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]. The pressure envelopes obtained with and without surge tank modification in case of pump power failure at 420 MW and minimum expected water level 1210 masl are presented in Figure 6. 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.

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].

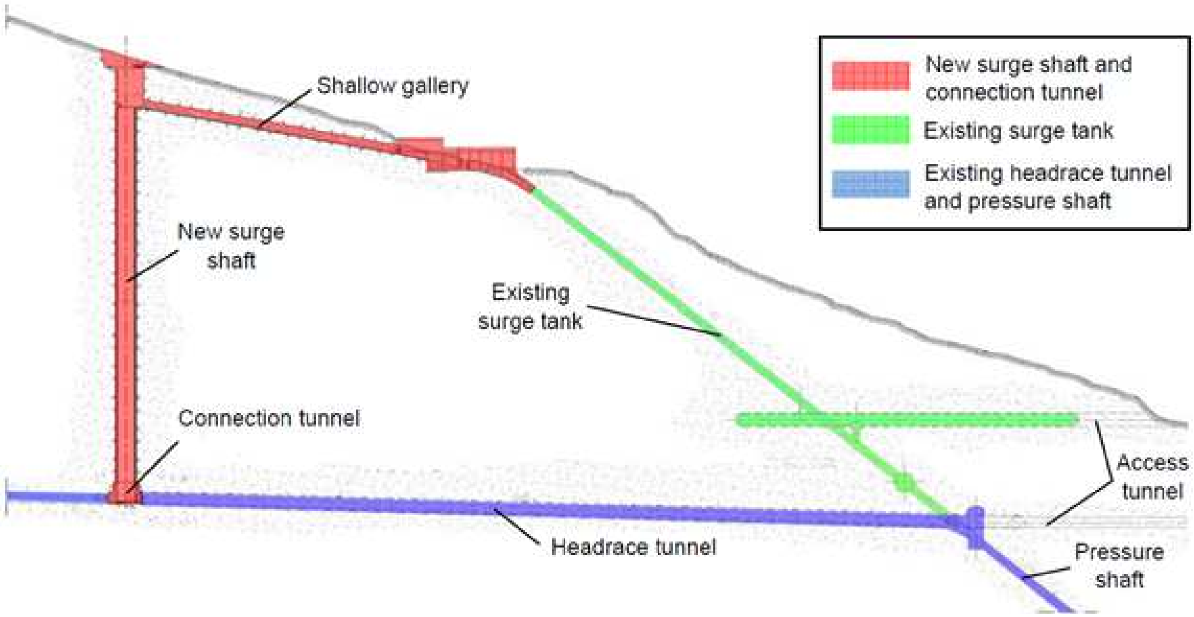

Figure 4. New surge tank cross section view, [3].

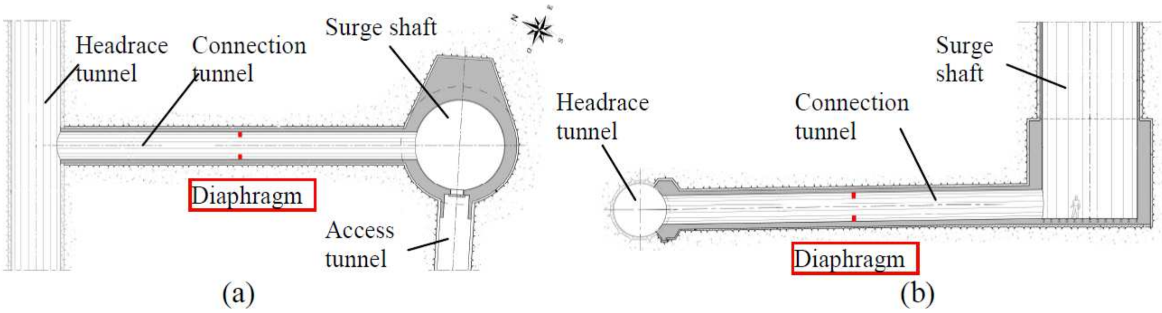

Figure 5. The new surge shaft and the connection and headrace tunnels; (a) Plan view; (b) Longitudinal section. The diaphragm inside the connection tunnel is also shown, [3].

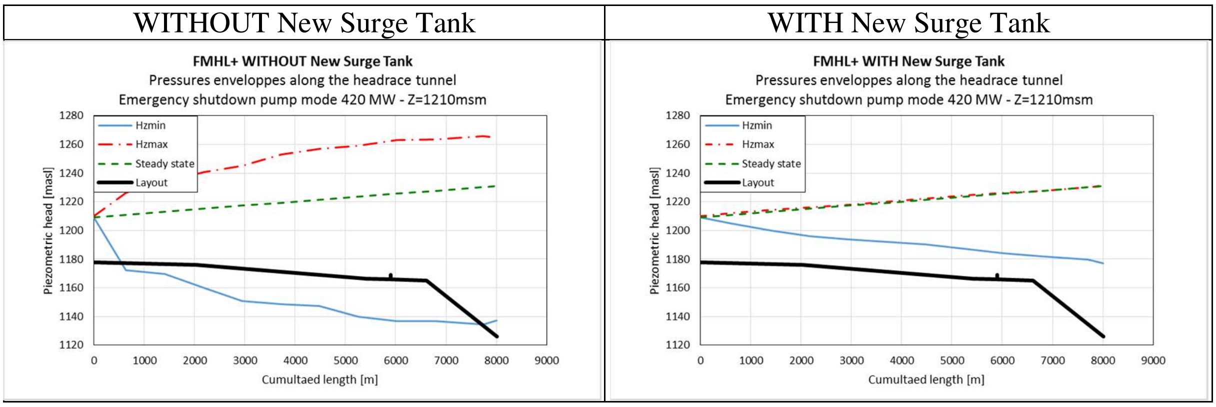

Figure 6. Minimum and maximum piezometric head envelopes in the headrace tunnel obtained with (left) or without (right) the new surge tank in case of emergency shutdown in pumping mode at 420MW and Z=1210 masl.

3. Hydro-Clone digital monitoring system for commissioning

3.1. General description

The Hydro-Clone is a 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 components of the plant, using the SIMSEN software [9], [10], [16], [19] and existing key monitoring points. 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;
- 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 alarms based on real-time and ahead-of-time analysis;
    - display of relevant on-line information of the health condition of the HPP;
    - communication with archival storage system.

As illustrated in Figure 7, the numerical simulation model benefits from measured boundary conditions, such as upper and lower reservoir water levels and injectors and pump discharge valve openings, to reproduce with high accuracy the dynamic behaviour of the hydraulic system. 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 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.

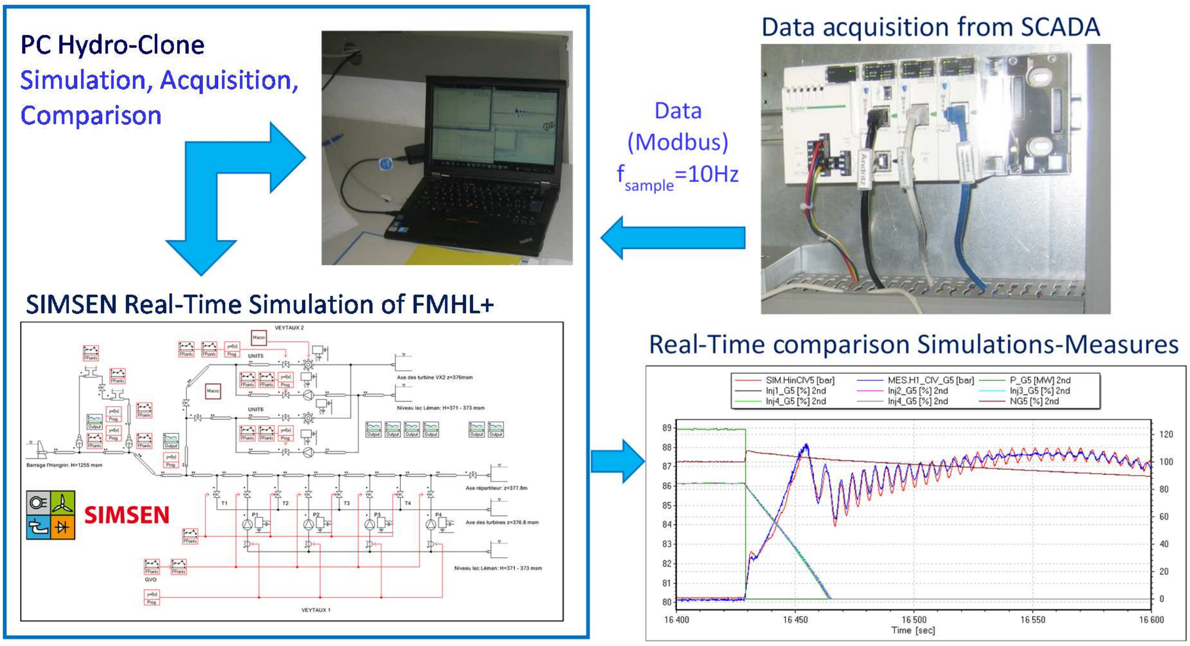

Figure 7. Hydro-Clone as used for the commissioning of Veytaux II new 120 MW units.

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 December 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 7 includes 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 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.

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. Transient tests of the new power house

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, [14], as well as for the commissioning of the new 120 MW Units 5 and 6 in June-December 2016 to compare in Real-Time simulation results with on-site measurements. 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. Figure 8 presents the comparison between Real-Time simulation results and on-site measurements in case of Emergency Shutdown in turbine mode at +428 MW in operation and in pump mode at -420 MW both with 5 units in operation.

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 8 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. The very good agreement of the pressure in the headrace tunnel was 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.

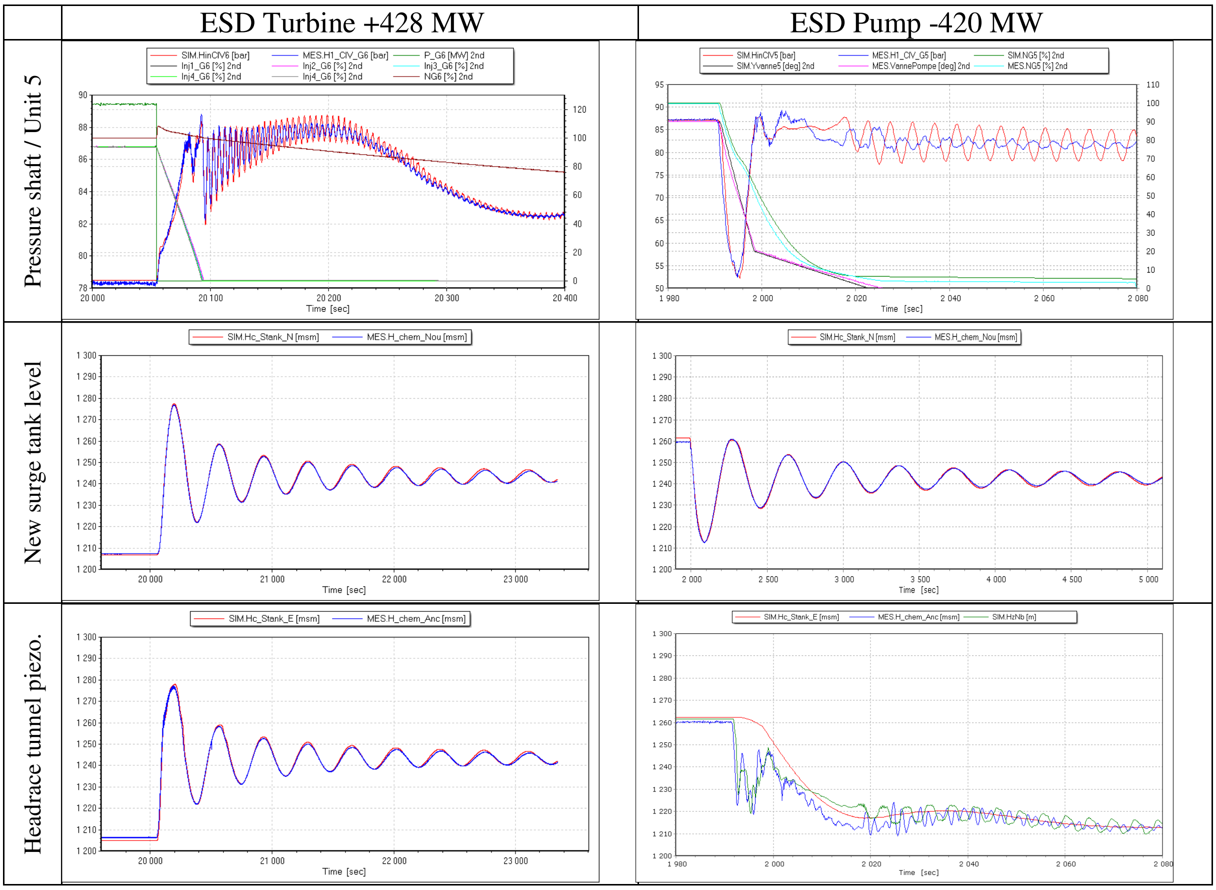

Figure 8. Comparison between Real-Time simulation results (red) and on-site measurements (blue) obtained during hydraulic transient tests performed for the commissioning of the new unit 5 in June 2016 in case of turbine and pump emergency shutdown (ESD) for different initial power levels.

5. Conclusion

The increase of the total capacity of the FMHL pumped-storage power plant from 240 to 420 MW achieved 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 [3], [11].

The commissioning of this new surge tank in November-December 2014 was an important step for the FMHL+ project and required particular attention, [14]. 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 Units 5 and 6 in June to December 2016 further confirmed the appropriate transient response of the new surge tank with transient tests performed at +428 MW in turbine mode and -420 MW in pumping mode. Very good agreement was also obtained between Real-Time simulations and on-site measurements.

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 is fully in operation since January 2017. 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 represents a major asset to contribute to power network stability in a constantly changing electricity market.

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