

TRANSIENT ANALYSIS OF FMHL+ PUMPED-STORAGE POWER PLANT AND NEW SURGE TANK DESIGN

Calculs Transitoires Hydrauliques pour l'Aménagement de Pompage-Turbinage de FMHL+ et Dimensionnement de la Nouvelle Cheminée d'Equilibre

Christophe Nicolet¹, Jean-Pierre Taulan², Jean-Michel Burnier³,
Monique Bourrilhon², Gaël Micoulet⁴, Alain Jaccard⁴

¹ Power Vision Engineering sàrl, Ch. des Champs-Courbes, CH-1024 Ecublens, Switzerland
christophe.nicolet@powervision-eng.ch

² EDF-CIH, Centre d'Ingénierie Hydraulique, Savoie Technolac, 73373 Le Bourget-du-Lac, France
jean-pierre-externe.taulan@edf.fr, monique.bourrilhon@edf.fr

³ STUCKY SA, Rue du Lac 33, CH-1020 Renens VD, Switzerland
jmburnier@stucky.ch

⁴ ALPIQ Suisse SA, Ch. de Mornex 10, CH-1001 Lausanne, Switzerland
gael.micoulet@alpiq.com, alain.jaccard@alpiq.com

ABSTRACT

FMHL (Forces Motrices Hongrin-Léman SA) is the Owner of Veytaux power plant which belongs to the shareholders Romande Energie SA, Alpiq Suisse SA, Groupe E SA and City of Lausanne. 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 power house Veytaux II to be operated in parallel to the existing Veytaux I power house 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 was made possible in FMHL+ project by modifying the existing surge tank. Such modification 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.

KEY WORDS

Water Hammer, Transient Analysis, Pumped-Storage Extension, Ternary Units, Surge tank modification.

RESUME

FMHL (Forces Motrices Hongrin-Léman SA) appartient aux actionnaires Romande Energie SA, Alpiq Suisse SA, Groupe E SA et la Commune de Lausanne. L'aménagement hydroélectrique de Hongrin-Léman est un aménagement de pompage-turbinage d'une puissance de 240 MW situé dans le Canton de Vaud, en Suisse, faisant l'objet d'une augmentation de la puissance installée à 480 MW dont 60 MW de réserve. Ce projet, nommé FMHL+ comprend la réalisation d'une nouvelle centrale de pompage-turbinage Veytaux II de 240 MW connectée sur la même adduction hydraulique. L'augmentation d'un aménagement hydroélectrique de 240 à 420 MW en réutilisant la même galerie, et la même conduite forcée sous une chute de 878 mCE, représente un défi technique important du point de vue des transitoires hydrauliques. Cette augmentation a été rendue possible grâce à une modification importante de la cheminée d'équilibre qui consiste à ajouter un nouveau puits vertical de 170 m de haut et 7.2 m de diamètre connectée à la galerie d'amenée. Ces modifications ont nécessité d'importantes études de transitoires hydrauliques considérant des cas de charge normaux, exceptionnels et accidentels pour les modes de fonctionnement de pompage, turbinage et de court-circuit hydraulique.

MOTS-CLEFS

Coup de bélier, transitoires hydrauliques, augmentation de puissance, pompage-turbinage, groupes ternaires, modification de cheminée d'équilibre.

1. INTRODUCTION

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), belonging to the shareholders Romande Energie SA, Alpiq Suisse SA, Groupe E SA and city of Lausanne, decided to extend the capacity of the existing Hongrin-Léman pumped-storage scheme.

Alpiq Suisse SA (Alpiq), which acts as the Owner's representative, is in charge of the supervision of the study and the implementation of the extension project. The existing power plant is operated by HYDRO Exploitation SA. 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 m³ at 1255 m a.s.l.) and Léman Lake (89'000 Mio m³ 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 Léman Lake near the city of Montreux.

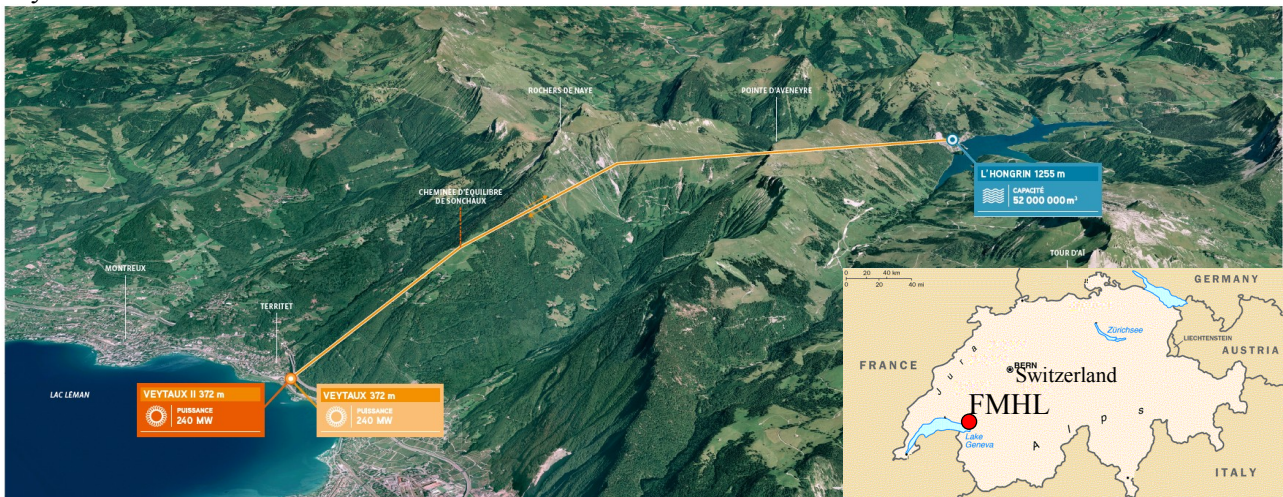


Figure 1: Location of the FMHL pumped-storage plant (right) and general layout (left) (red: new power station)

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 will be 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.

Increasing the output and input power of an existing hydroelectric scheme from 240 to 420 MW using the existing headrace tunnel and the pressure shaft with a maximum gross head of 878 mWC is a challenging task as far as the hydraulic transients are concerned. This 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, which is the subject of this article. Such modification 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.

This article presents the different steps of the transient analysis performed for the FMHL+ project and new surge tank design including: (i) simulation model validation of the existing 240 MW FMHL power

plant, (ii) identification of critical load cases of the 420 MW FMHL+ power plant, (iii) variant study for the surge tank modification, (iv) design of the new surge tank, (v) transient analysis for the final surge tank design validation. The paper is focusing on problematic like low pressure risk in headrace tunnel and surge tank overflow or emptying risk,

2. DESCRIPTION OF THE HONGRIN-LÉMAN POWER PLANT

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 power house with installed capacity of 240 MW connected downstream to the Léman Lake with minimum water level of 371 masl. The new Veytaux II underground power house is to be located next to the existing one with an installed capacity of 240 MW, see Figure 3, and will be connected to the existing pressure shaft. The two power house 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 [5], and a detailed description of the new electromechanical equipment is provided in ref [3]. The new multistage pumps of Veytaux II are provided by VOITH Hydro, see ref [4], while the new synchronous motor-generator and the new Pelton turbines are provided by ANDRITZ Hydro. The valves are provided by the consortium ANDRITZ Hydro / D2FC.

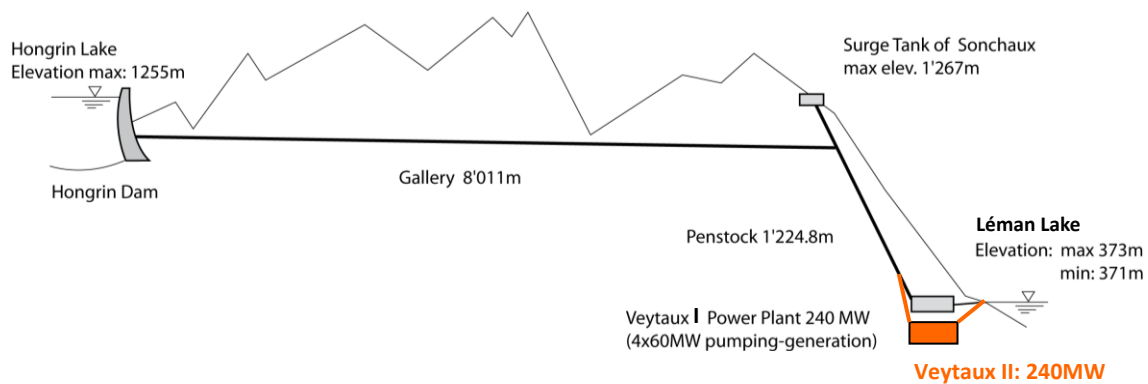


Figure 2: Layout of the FMHL power plant with existing Veytaux I power house with 240 MW total capacity and the Veytaux II power house with additional 240 MW.

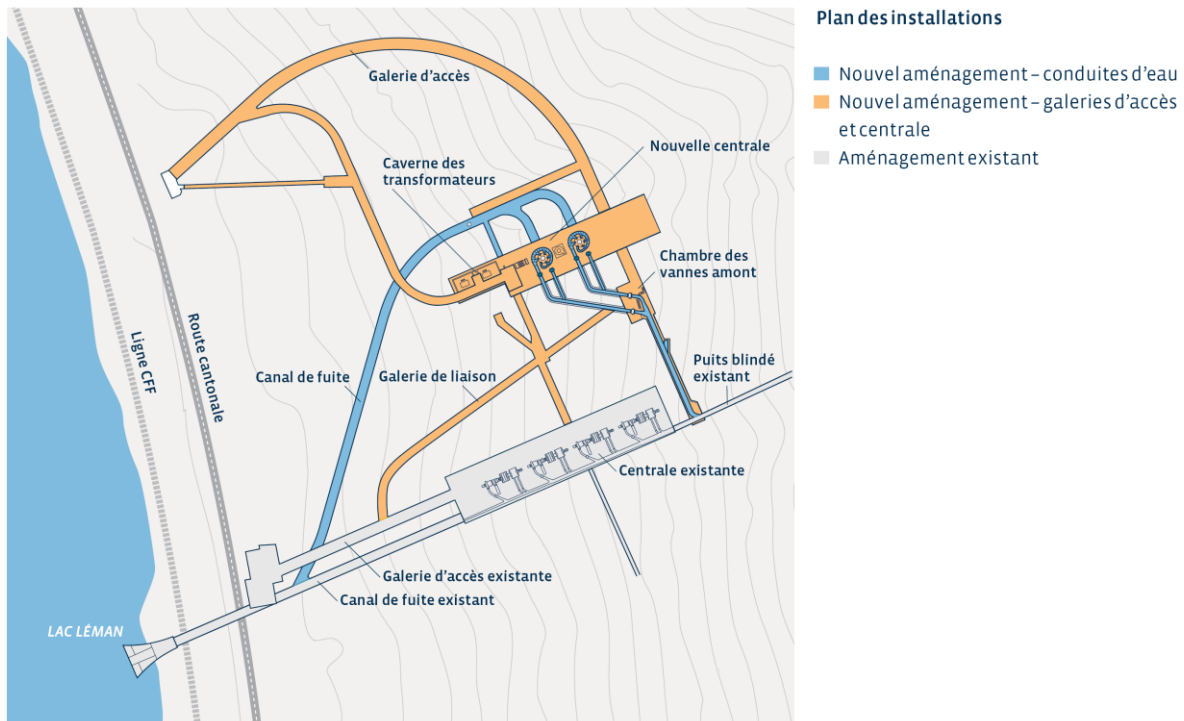


Figure 3: Top view of the existing (gray) and new (colourful) power houses Veytaux I and Veytaux II, [3].

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

	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)	

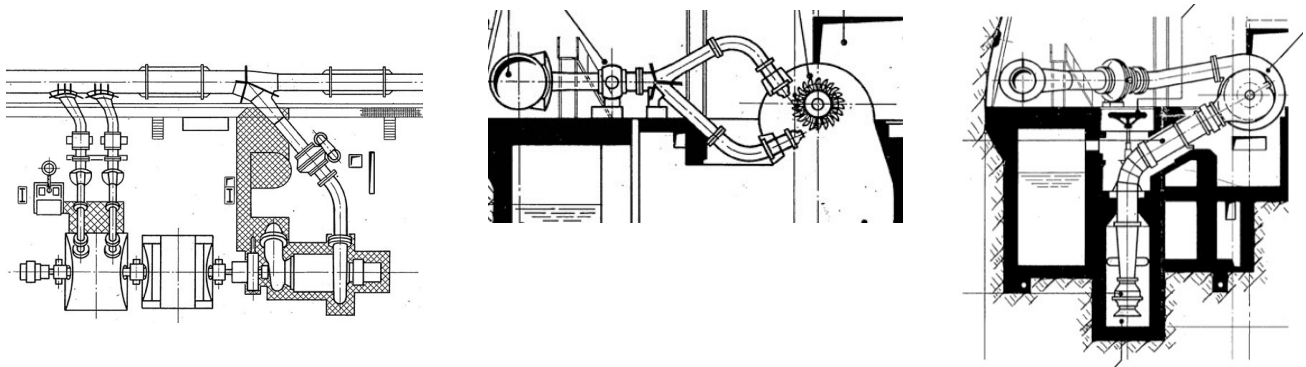


Figure 4: Top view of one Unit arrangement (left) and cross section view of the turbine (middle) and of the pump (right) of Veytaux I Power House, source FMHL.

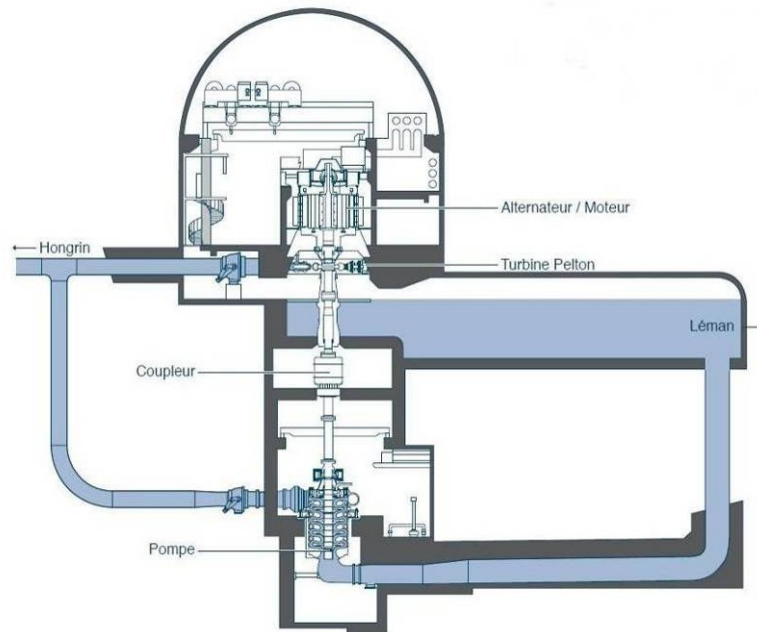


Figure 5: Cross section view of the ternary Unit of Veytaux II Power House, [3].

3. HYDRAULIC TRANSIENT CHALLENGES IN FMHL+ PUMPED-STORAGE EXTENSION

The total installed capacity of the FMHL+ power plant is of 480 MW, but only 420 MW will be used for generating and pumping operation, with 60 MW reserve. The increase of capacity from 240 to 420 MW of an existing hydroelectric power plant is a challenging task with respect to the hydraulic transients phenomena induced by both generating and pumping mode of operations. The generating and pumping discharge are respectively increased from 32 to 57 m³/s and from 24 to 43 m³/s. The key problematic related to this considerable discharge increase to be addressed during the transient analysis are the followings:

- increase of pressure shaft over pressure in generating mode during emergency shutdown;
- possible increase of pressure shaft over pressure in pumping mode in case of power failure;
- increase of surge tank maximum water level in generating mode during emergency shutdown;
- decrease of surge tank minimum water level in pumping mode in case of power failure;
- decrease of surge tank minimum water level in generating mode during start-up;
- increase of surge tank maximum water level in pumping mode during start-up;
- decrease of the minimum pressure in the headrace tunnel and at the penstock top in pumping mode in case of power failure;
- complex transient phenomena resulting from hydraulic short circuit operation of the units of Veytaux II and also between the two power houses, with all possible combinations of operating mode and mode changes (or transition mode);
- validation of existing units operation in upgraded configuration, and adaption of existing units operating laws if necessary.

In order to maximize the lifetime of the aging existing equipments and pressure shaft, it was decided, to restrict the maximum allowable pressure in the pressure shaft, to the maximum overpressure which may result from normal operation of Veytaux I power house in the existing configuration. The normal operation comprises also emergency shutdown in pumping and generating mode of operation. Thus, the maximum allowable pressure in the pressure shaft considered for FMHL+ project was significantly lower than the design pressure of the original power plant.

To achieve this goal, a detailed transient analysis was undertaken at very early stage of the project by EDF in collaboration with Power Vision Engineering as owner's expert. After the electromechanical lot awards, extensive transient analysis was performed by the pump manufacturer, i.e. VOITH Hydro, see Ref [4], once the new multistage pump characteristics were obtained from reduced scale model testing.

In this study, 32 operating load cases have been simulated and documented, covering the different operating possibilities given by 5 groups and three operating modes taking into account: pumping mode, turbine mode and hydraulic short-circuit operation. These cases have been classified in three types :

- Normal cases: resulting from normal operation such as unit loading, normal stop, emergency shutdowns and power failures from steady state operation;

- Exceptional cases: all cases including worst cases combination such as unit loading followed by emergency shutdowns at worst moment with respect to the surge tank water level oscillations, or resulting from the worst tripping sequence of several units;
- Accidental cases: all cases resulting from dys-functioning such as distributor or valve non closing during a load rejection case, or pipe burst but also all cases with power network large frequency deviation.

The maximum permissible value of pressure shaft over pressure or minimum permissible values of pressure in headrace tunnel are more severe for normal and exceptional cases than for accidental load cases.

4. MODELLING AND VALIDATIONS

In case of extension of the capacity of existing power plants, it is important to dispose of a validated model of the existing power plant, in order to minimize the uncertainties of the transient analysis for the power extension. Indeed, the computation should take into account safety margins as well as error margin. Error margins are calculated as a percentage of a value variation during the studied operation, they are used to cover uncertainties on input data and error resulting from numerical modeling. Safety margins are additional margins to respect between the permissible value and the result of the simulation corrected with the error margin, in order to account for unforeseen additional load cases.

For new power plants, it is possible to minimize uncertainties using a step by step validation procedure of the input data and hypothesis based on model testing and CFD computations. In addition, extending safety margin is always possible by basic layout modifications in new project. In existing power plants, increasing safety margin results either in a reduction of the expected operating range and thus of the related project viability or in complex layout modifications. In addition, error margin can become significant as it can be difficult to make available all electromechanical data and identify all power plant and equipment modifications over 40 to 50 years of operation. Therefore, the validation of the simulation model of the existing power plant of FMHL was addressed with special care, and both generating and pumping mode have been subject to validations.

The main difficulties were found for validating the model in pumping mode, due to multiple sources of uncertainties related to the spherical valve characteristic, to pump characteristics and to total inertia uncertainties. A thorough search at owner's archives and at the pump manufacturer archives, i.e. Sulzer Pumps, enabled to remove the main sources of doubts and achieve satisfactory validations of the Veytaux I configuration. The validations are illustrated in Figure 6 and Figure 7 by the comparisons between simulations results and on-site measurements obtained respectively for turbine mode and pumping mode.

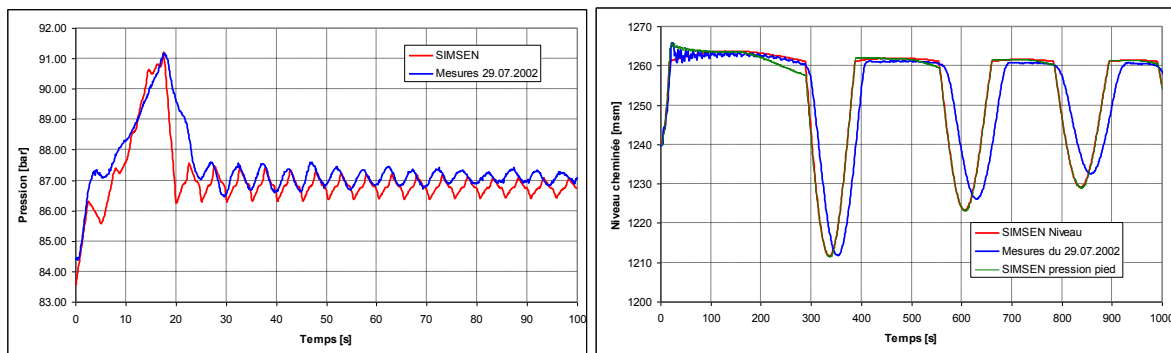


Figure 6: Comparison of measurements and simulation results of penstock bottom pressure (left) and of surge tank water level (right) in case of 4 units emergency shutdown in turbine mode.

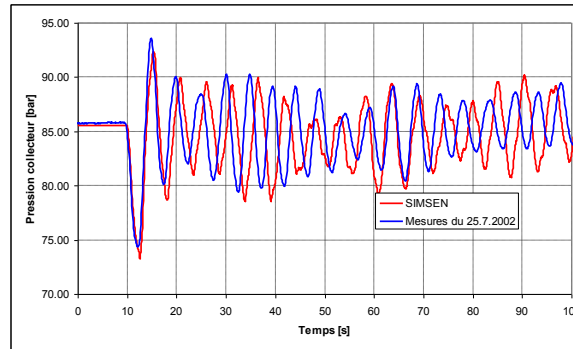


Figure 7: Comparison of measurements and simulation results of penstock bottom pressure in case of 1 unit emergency shutdown in pumping mode.

5. SURGE TANK MODIFICATIONS

5.1 Gallery low pressure risk problematic

Among the expected risks listed in section 3 resulting from capacity increase, for FMHL, the most problematic case was found to be related to the pump power failure at 420 MW, without any surge tank modification, and related risk of low pressure in the headrace tunnel. The problem was even identified from the first computation performed in pumping mode at 420 MW for the maximum Hongrin water level, which results are presented in Figure 8. Indeed, the increase of discharge in pumping 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, and the headrace profile presents a slope discontinuity after a flat zone at around 80% of its length, that increases the cavitation problem. As it could be noticed in Figure 8, this fast drop of pressure at one end of the gallery induces pressure oscillations in the headrace tunnel characterised by the first and second hydroacoustic natural frequency of the tunnel. As a consequence, the minimum and maximum pressure envelope found in the headrace tunnel differs considerably from a straight line which would results from the mass oscillation alone.

These results show that the dynamic behaviour of the galleries may play a considerable role in the minimum pressure calculated in the gallery itself. The contribution of the headrace tunnel natural frequencies to the minimum pressure obtained in the tunnel represents here about 10 mWC, i.e. approximately the safety margin usually considered for this type of calculations. Often, the headrace tunnels are modelled with rigid column model in order to reduce computation time. In these calculations, the tunnel was modelled considering elastic model of the tunnel, enabling to account for pressure fluctuations resulting from the tunnel free oscillation response.

The results obtained here at maximum Hongrin water level show a low pressure region in small part of the headrace tunnel featuring a slope change, while the same computation performed for the minimum water level lead to the identification of cavitation zone extending over more than 30% of the tunnel which is not acceptable. Besides low pressure risk in the gallery, the surge tank modification was also necessary with respect to the maximum water level.

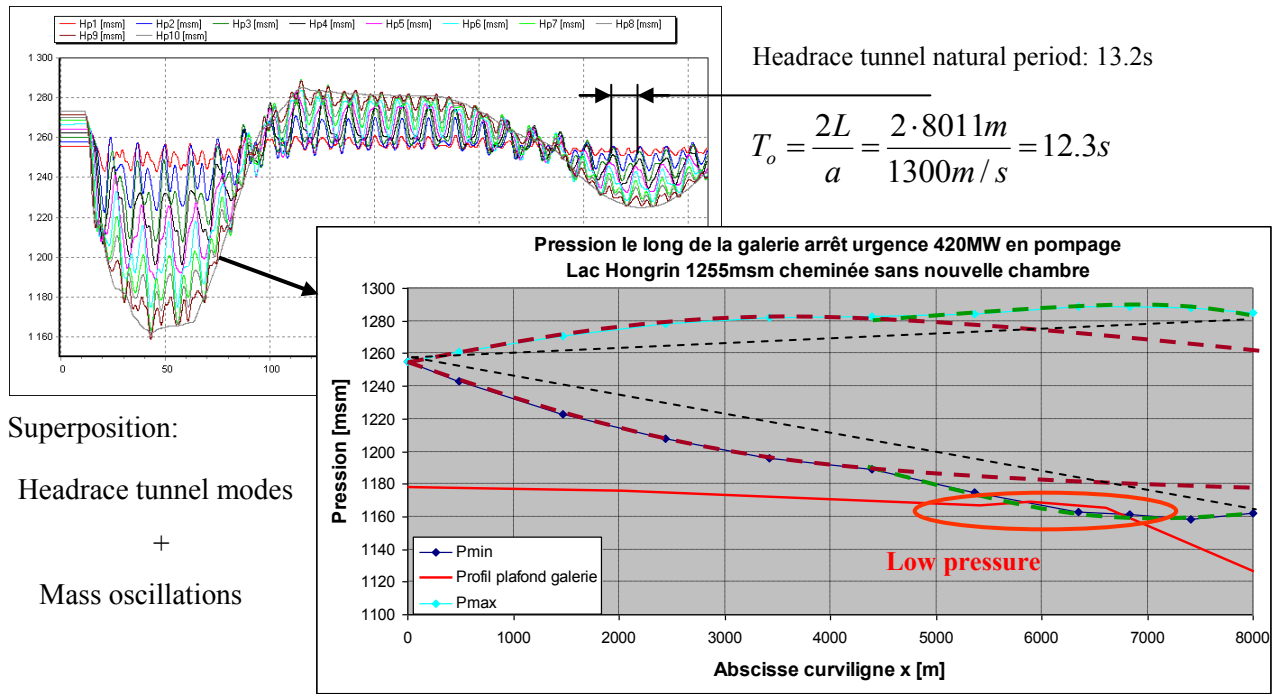


Figure 8: Simulation results of the time evolution of pressure at different location along the headrace tunnel (top) and the related pressure envelopes along the headrace tunnel (bottom) resulting from pump power failure at 420 MW for the maximum water level of the upper reservoir.

5.2 New surge tank configuration investigations

The resolution of the headrace low pressure problem identified in pumping mode requires either a considerable limitation of the pumping power as function of the upper reservoir water level, or a modification of the surge tank. As the first solution would have jeopardize the project profitability, the second solution was addressed taking into account geologic, execution, outage and planning constraints in order to find the most cost-effective solution, see ref [1], [7], [8], [9].

Figure 9 presents the volumetric representation of the solution considered for simulations of FMHL+ power plant with surge tank modifications. Among all these solution, the most hydraulic effective solution was the solution of a new vertical surge tank connected in the lower part directly to the headrace tunnel. This solution also offers the advantage of being effective at any upper reservoir water level. The others solution offered obvious constructive advantages, but also lead to strongly non-linear behaviour which consequences become very difficult to evaluate with respect to the numerous possible operating sequences offered by a 5 units pumped-storage power plant with ternary units with possible hydraulic short circuit.

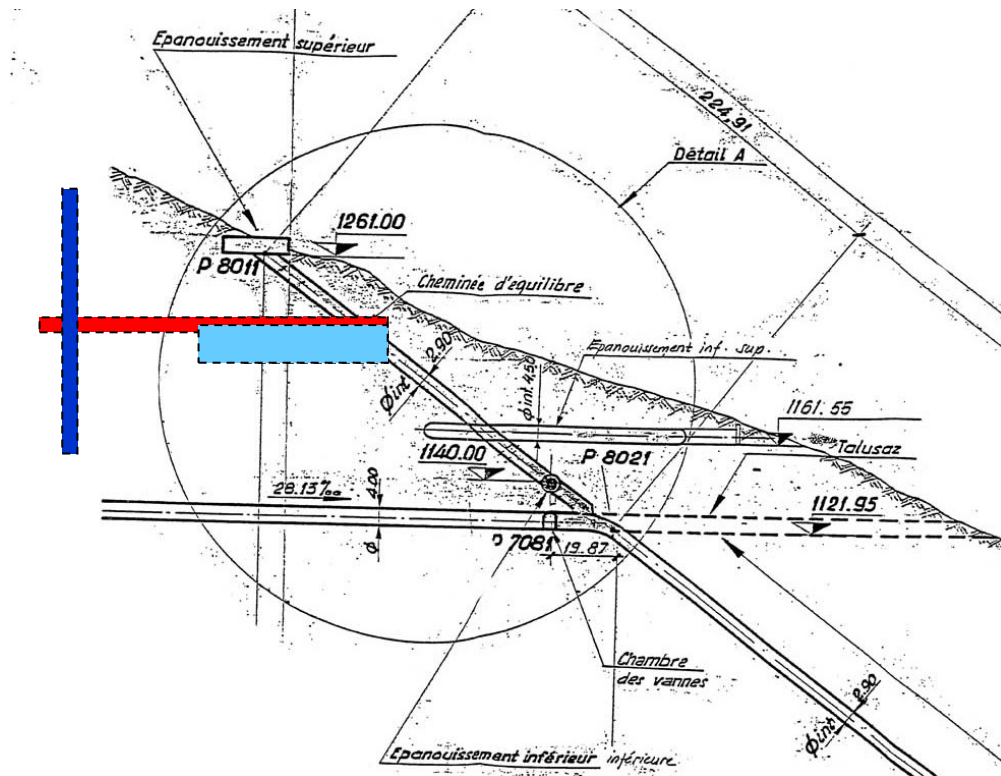


Figure 9: Variant study for surge tank modifications (in black the existing expansion chambers, colourful schematic view of the variants).

5.3 Final solution of surge tank modifications

Figure 10 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 11, 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 the SIMSEN simulation model of Figure 12 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. The load case 1 was found to be the most restrictive according to its normal nature requiring higher safety margin than the load case 2 featuring an accidental nature, allowing a reduction of the safety margin.

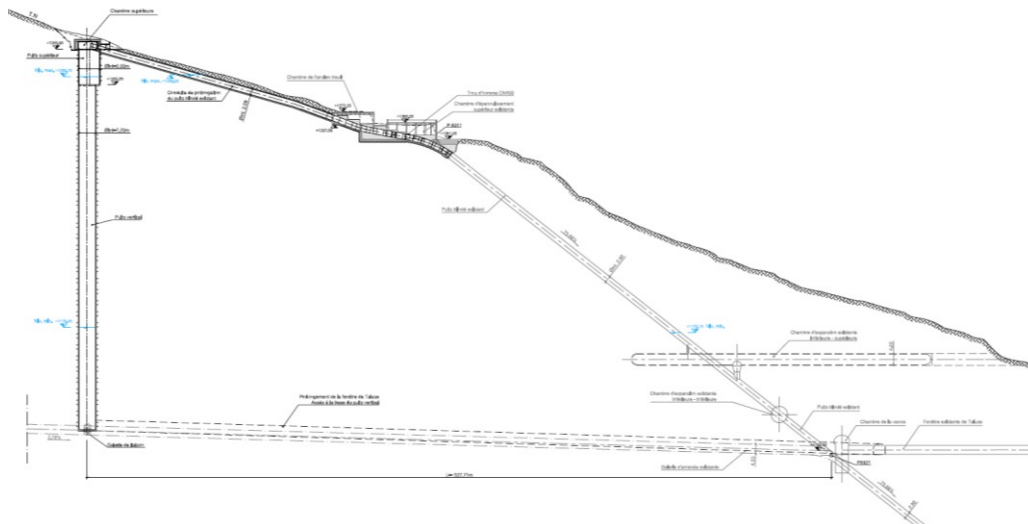


Figure 10: New surge tank cross section view.

Figure 13 presents the simulation results obtained with the new surge tank in case of emergency shutdown at 420 MW for both turbine mode of operation at maximum upper reservoir water level, and for pumping mode at minimum upper reservoir water level. The time evolution of the water level in the surge tanks as well as the pressure in the headrace tunnel show a stable and smooth transient behaviour. The representation of the minimum pressure envelopes obtained along the headrace tunnel for the load cases 1 and 2, see Figure 14, confirms the effectiveness of the new surge tank, and evidences that pressure oscillations in the tunnel at natural frequencies does not occur anymore.

Once the diaphragm head losses were optimised from the hydraulic point of view, physical model tests of the surge tank have been carried at the EPFL Laboratory of Hydraulic Constructions to determine the geometry of the diaphragm, see [2], 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. It was found that the worst load case with respect to maximum water level in the surge tank is obtained for hydraulic short circuit operation, when all pumps are in operation, and input power is modulated by the two Pelton turbines from Veytaux II and assuming that all injectors are closing and that a pump power failure occurs at the worst moment, see [4].

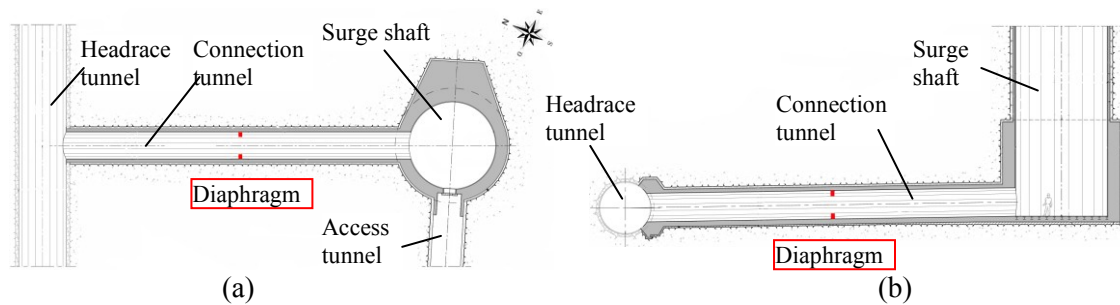


Figure 11: The new surge shaft and the connection and headrace tunnels; (a) Plan view; (b) Longitudinal section. The diaphragm inside the connection tunnel is also shown, [2].

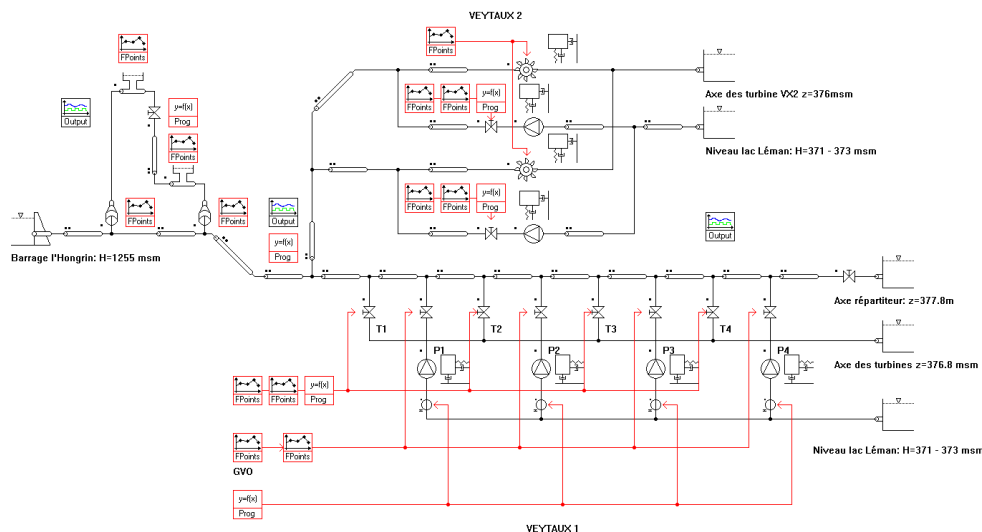


Figure 12: SIMSEN simulation model including the Veytaux II power house and the new surge tank.

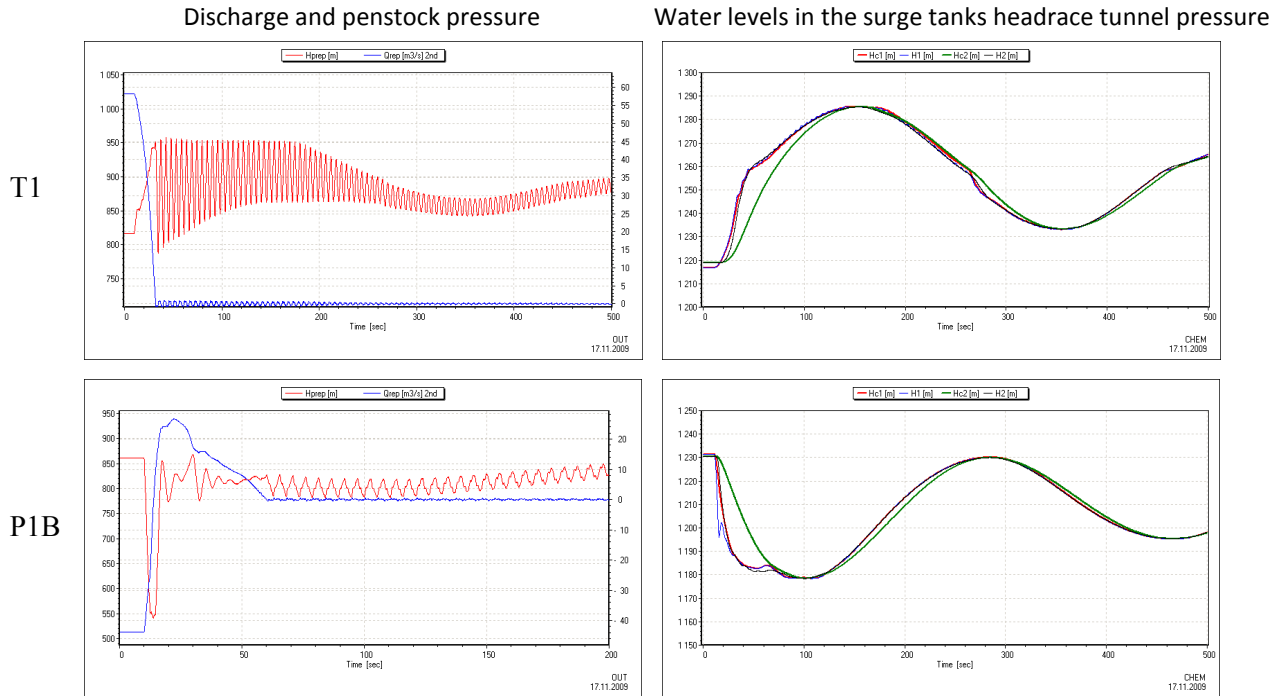


Figure 13: Simulation results in turbine mode (top) and pumping mode (bottom) in case of emergency shutdown at approx. 420 MW at respectively maximum and minimum upper reservoir water level; time history of penstock bottom pressure and discharge (left) and surge tanks (existing and new one) water levels and gallery pressures (right).

FMHL+

Minimum pressure along the headrace tunnel in case of pump emergency shutdown at 420MW and 1210masl for optimal diaphragm head loss

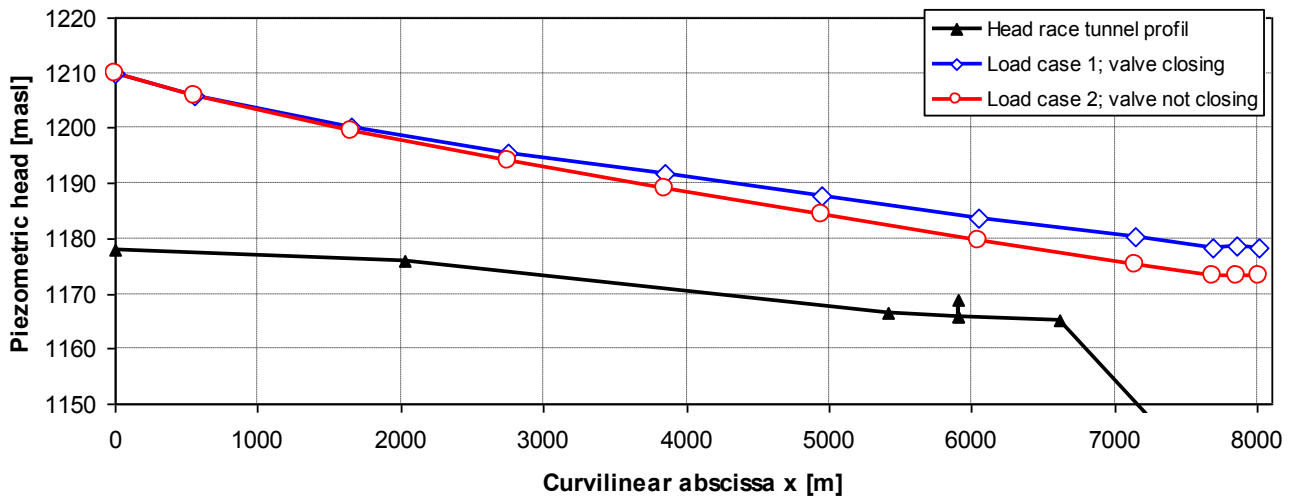


Figure 14: Minimum pressures along the headrace tunnel in case of emergency shutdown in pumping mode at minimum upstream water level, at 420 MW (load case 1) and at 420 MW with one of the pump discharge valve of Veytaux II not closing (load case 2) obtained with the optimal diaphragm head losses.

7. CONCLUSIONS

Increasing the total capacity of the FMHL pumped-storage power plant from 240 to 420 MW requested a detailed transient analysis at early stage of the project. Among the different problematic addressed in this analysis, the low pressure risk in the headrace tunnel occurring in case of pump power failure at low upper reservoir appeared to be the most critical case for FMHL power plant.

This problem was solved by modifying the surge tank with the introduction of a new vertical surge shaft with optimised head losses achieved by a diaphragm.

Several aspects have been found to be decisive in the identification and resolution of the problems related to transient phenomena, and can be summarised as follows:

- pay a particular attention to validate the model of the existing power plant in generating and pumping mode in order to minimize uncertainties associated with existing equipments;
- use appropriate models for the headrace tunnel taking into account the elastic behaviour of the tunnel which appear to play a significant role with respect to the low pressure risk in the tunnel;
- have several independent transient computations performed in parallel, here performed with different software by EDF and Power Vision Engineering;
- minimize uncertainties by confirming step by step, as much as possible input data of the model, based on hydraulic machine model testing, surge tank physical modelling, or maybe even CFD computation if needed;
- have a good collaboration between the Owner, the Engineer, the experts and the electromechanical equipment suppliers.

8. ACKNOWLEDGMENTS

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