

Simultaneous transient operation of a high head hydro power plant and a storage pumping station in the same hydraulic scheme

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Abstract. This paper presents an on-site experimental analysis of a high head hydro power plant and a storage pumping station, in an interconnected complex hydraulic scheme during simultaneous transient operation. The investigated hydropower site has a unique structure as the pumping station discharges the water into the hydropower plant penstock. The operation regimes were chosen for critical scenarios such as sudden load rejections of the turbines as well as start-ups and stops with different combinations of the hydraulic turbines and pumps operation. Several parameters were simultaneously measured such as the pumped water discharge, the pressure at the inlet pump section, at the outlet of the pumps and at the vane house of the hydraulic power plant surge tank. The results showed the dependence of the turbines and the pumps operation. Simultaneous operation of the turbines and the pumps is possible in safe conditions, without endangering the machines or the structures. Furthermore, simultaneous operation of the pumping station together with the hydropower plant increases the overall hydraulic efficiency of the site since shortening the discharge circuit of the pumps.

1. Introduction

As the energy market is changing with the introduction of renewable power resources, the role of hydropower in electrical grids stabilization is becoming more important. The need to regulate the grid requires more flexibility of the hydropower plants and pumping stations operation inducing transient operations. Transient regimes are usually caused by variations of the hydraulic machines operation like starts, stops, load variations and load rejections. It is necessary to analyze the transient operations to determine undesired pressure pulsations, in order to assure safe operation of the hydraulic power systems.

The study of transient regimes was performed using analytical and numerical methods. Investigations have been performed both numerically, using hydro-acoustic theory [1, 2, 3] and CFD technique [4, 5] and experimentally [6, 7, 8].



This paper presents an on-site experimental analysis of the simultaneous operation during transient regimes of a high head hydro power plant (HPP) and a storage pumping station (PS), in an interconnected hydraulic scheme. The analyzed hydropower site has a unique structure as the pumping station discharges the water directly into the hydropower plant's penstock. A detailed investigation was required by the energy market changes which led to a new operation scheme of the two plants. In the initial project the pumping station was designed to operate while the hydro power plant was not in operation. New demands of the energy consumption market forced the simultaneous operation of the two plants. An experimental study was undertaken to investigate the simultaneous operation of both plants, especially during transient operations. In the present work, the influence of different regimes is presented.

2. Power station and measuring program

2.1. Site description

The analyzed hydropower site consists in a high head HPP with two Francis units of 75 MW ($H_{HPP} = 470$ m, $Q_{HPP} = 2 \times 22.8$ m³/s), a PS with two double entry two stages centrifugal pumps of 10 MW ($H_{HPP} = 260$ m, $Q_{HPP} = 2 \times 3$ m³/s) and a hydraulic system, see figure 1. The HPP and PS are coupled through a series of pipes; thus the variation of the flow parameters in one plant influences the other plant.

The HPP water intake has a 3.7 m diameter and is 8500 m long. The HPP surge tank communicates with the intake through a 1.78 m diameter diaphragm. The lower chamber of the surge tank is a cylinder 6 m in diameter and 120 m high. The upper chamber has the shape of a truncated cone 18 m high, with an average diameter of 17 m. The penstock of the HPP has a 2.8 m diameter and is 750 m long.

The PS water intake has a 2.8 m diameter and is 6500 m long, with a double chamber surge tank of 50 m height. The PS discharge pipe has a 1.3 m diameter and is 340 m long [9].

A vane house couples the HPP water intake pipe and the penstock. The discharge pipe of the PS joins the HPP penstock downstream vane house.

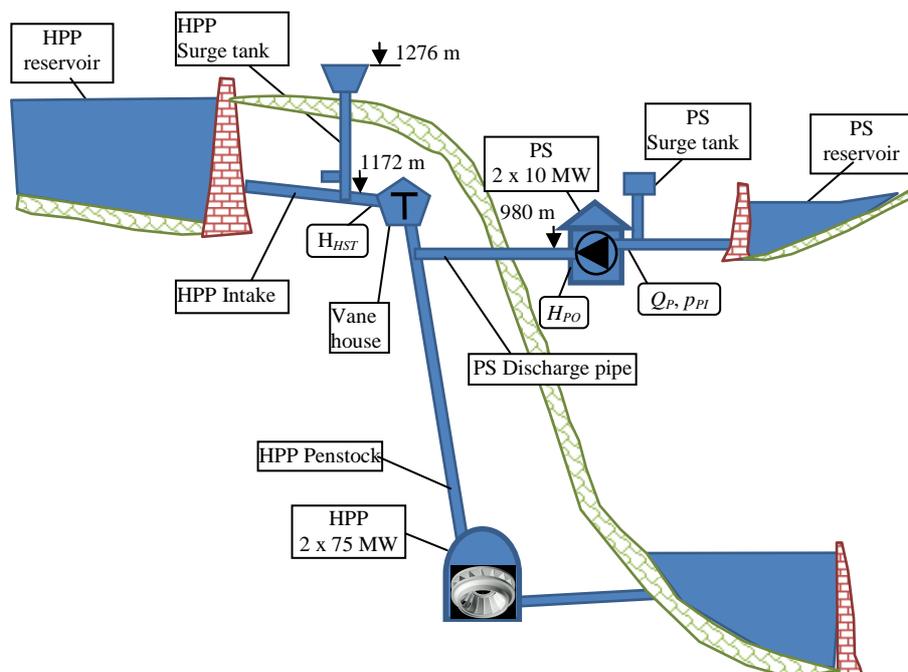


Figure 1. Hydropower scheme of the analyzed site.

2.2. Measuring program

The measuring program was chosen to investigate critical scenarios; sudden load rejections of the turbines, start-ups and stops with different combinations of the hydraulic turbines and pumps operation (table 1). The main concern was the maximum mass oscillation amplitudes in the surge tank which may be damaging for the pumps.

Stability and behavior of the hydraulic system under transient conditions depend upon the characteristics of all its parts. In order to have a reference over the pumps operation capacity (discharge and head), the experimental analysis started with the operations in the PS, while the HPP was shut-off. In this situation, the pumps are discharging the water up to the HPP reservoir; the total pump head includes the hydraulic losses for the 8500 m of the HPP intake. During simultaneous operation, the hydraulic circuit of the pumps is shortened, because the water is discharged in the HPP penstock, see figure 1. For the simultaneous operation, the analysis comprises starts and stops of the pumps with both turbines in operation. Then, the influence of the turbines maneuvers (start, stop, and sudden load rejection) over steady operation of the pumps was investigated.

Table 1. Measuring program^a.

Scenarios	Operation state	Turbine 1 (m ³ /s)	Turbine 2 (m ³ /s)	Pump 1 (m ³ /s)	Pump 2 (m ³ /s)
1 pump start-up	Start	0	0	2.3	0
	End	0	0	2.3	2.3
1 pump stop	Start	0	0	2.2	2.2
	End	0	0	2.2	0
1 pump start-up	Start	19.78	19.78	0	0
	End	19.78	19.78	2.6	0
1 pump stop	Start	19.78	19.78	2.7	2.7
	End	19.78	19.78	2.9	0
1 turbine stop	Start	18.75	18.75	2.8	2.8
	End	18.75	0	2.6	2.6
1 turbine stop	Start	19.78	0	2.8	0
	End	0	0	2.4	0
1 turbine load rejection	Start	18.63	0	2.4	0
	End	0	0	2.3	0
1 turbine load rejection	Start	18.63	0	2.35	2.35
	End	0	0	2.1	2.1
2 turbines load rejection	Start	19.90	19.90	2.8	0
	End	0	0	2.2	0

^a Discharge values are highlighted with bold for the units that are subjected to the operation regime change

2.3. Measured hydraulic parameters

Several parameters were simultaneously recorded for analysis, see figure 1. The water discharge at the PS intake (Q_P) was measured with an ultrasonic flow meter (1% accuracy). The water levels were determined using relative pressure transducers (0.5% accuracy) at the pump inlet section (p_{PI}), at the pumps outlet section (H_{PO}) and at the vane house for surge tank level determination (H_{HST}).

The water level in the HPP surge tank was an important parameter to determine, in order to evaluate if the pumps design capacity could handle the mass oscillations resulting from transient operations. According to the HPP design, the maximum water level must not exceed 1276 m elevation to avoid overflow of the HPP surge tank. To avoid air entrapment in the hydraulic system through the HPP surge tank, the minimum water level should be kept above 1172 m elevation.

The data was recorded with two synchronized acquisition systems; one in PS and one at the valve housing. The measurements were performed for time periods ranging from 10 to 30 minutes.

3. Results

Experimental results are presented as time variation of the measured parameters: inlet pump pressure, pump discharge, outlet pump pressure and pressure level in the HPP surge tank. For a better interpretation, the last two are plotted as water elevation levels, H_{PO} , H_{HST} .

3.1. Pumping station operation

Before analyzing the interaction between the turbines and the pumps operation during transients, the PS single operation was investigated. In this case the pumped water has to be transported up to the HPP's reservoir, through the HPP's intake 8.500 m long.

Figure 2 presents the start-up of one pump while the other one was in operation (at time 50 s). The PS discharge doubled (from 2.3 to 4.6 m³/s) and became stable in 2.5 minutes.

The shutdown of one pump while both operating (figure 3), shows the corresponding discharge decrease, but the stabilization lasted for a longer time. When the pump was completely shut off ($t = 100$ s) the outlet pump pressure had a sharp decrease due to the complete closing of the outlet vane, followed by a fast increase at $t = 120$ s due to the inlet pressure increase. The surge tank level H_{TST} and the pressure at the pump outlet H_{PO} have a similar shape with a phase shift. After 4 minutes, the discharge was still oscillating. Also, pressure variations had higher amplitudes and shorter periods, in all measurement sections.

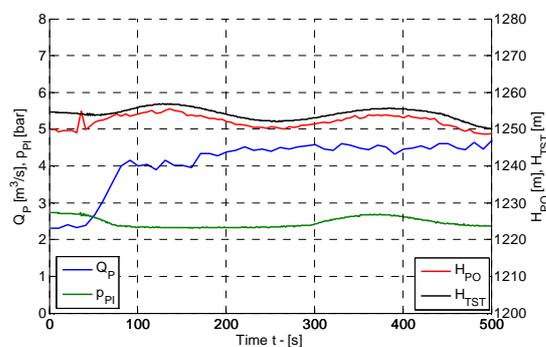


Figure 2. Start-up of one pump while one pump is in operation.

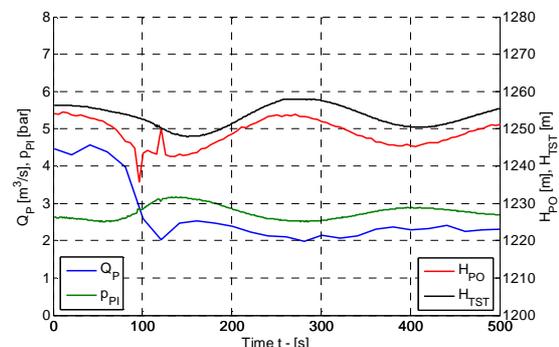


Figure 3. Shut down of one pump while both pumps operate.

The starting of the pumps while both turbines operate is important to be analyzed because the pumped discharge will be diverted directly in the HPP penstock, without being transported to the HPP reservoir. Also, the necessary net pressure head is decreased with the HPP intake hydraulic losses, which is reflected in the pumped discharge. As it can be seen in figure 4, the discharge of one pump with both turbines in operation is 2.7 m³/s; larger compared to a single pump operation without any turbine in operation (2.2 – 2.3 m³/s). The flow stabilized faster, in 1.5 min.

If all four units were in operation, the pumped discharge was also increased compared to the single operation of the PS, 5.4 m³/s instead of 4.6 m³/s. The shut off of one pump (figure 5), caused small variations of the PS outlet pressure and surge tank level with just one oscillation and a fast attenuation.

In all cases, the pressure at the PS inlet section had different oscillation amplitudes and periods, than the rest of the parameters, due to the PS surge tank influence.

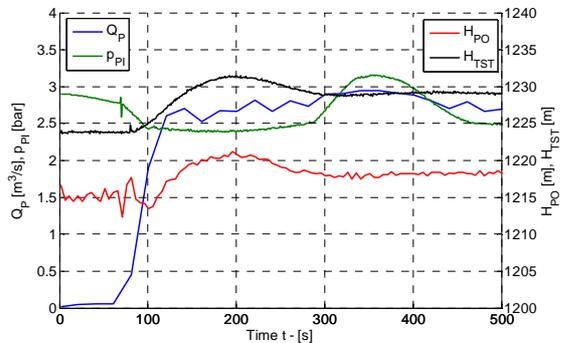


Figure 4. Start-up of one pump with both turbines in operation

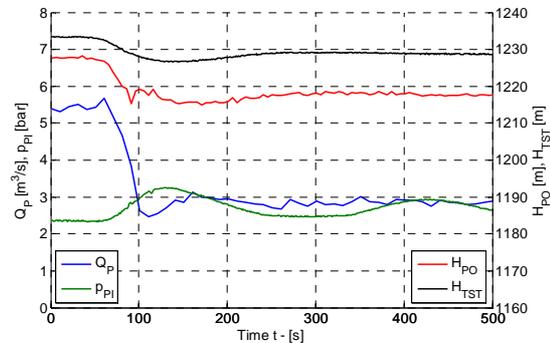


Figure 5. Shut down of one pump while one pump and both turbines are in operation

3.2. Hydraulic turbines operations

Turbine normal shut off operations and undesired sudden load rejection were the next scenario investigated. Such type of operation involves pressure increase in the system for the PS. Also, during sudden load rejection, water hammer pressure waves travel in the entire system, possible affecting the operation regime of the pumps.

If all four units were in operation and a turbine was shut off (figure 6), the increase of water level in the HPP surge tank (equivalent to 2.55 bar) was accompanied by an important decrease of the PS discharge ($1.5 \text{ m}^3/\text{s}$) for a 5 minutes period.

When a turbine was shut off while one pump and a turbine were kept in operation (figure 7), the level variation was higher (equivalent to 2.94 bar). The pressure oscillation had a similar period, and lasted more than 13 minutes. The pumped discharge decreased from 2.8 to $2.4 \text{ m}^3/\text{s}$ and stabilized after 8 minutes.

The oscillation period for normal stop of the turbines was 300 s, reaching a maximum elevation in the surge tank of 1260 m. This maximum level elevation was directly influenced by the geometry of the surge tank, the water volume flowing back from the turbines filling the lower chamber and the shaft, reaching up to the bottom of the upper chamber. Because the cross section of the upper chamber is larger than the section of the surge tank shaft, the water elevation curve becomes almost flat after it passes over the upper chamber inlet level at 1258 m (figure 6 and figure 7).

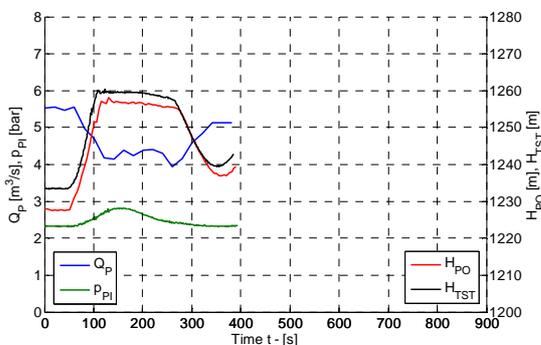


Figure 6. Shut off of one turbine when all four units were in operation

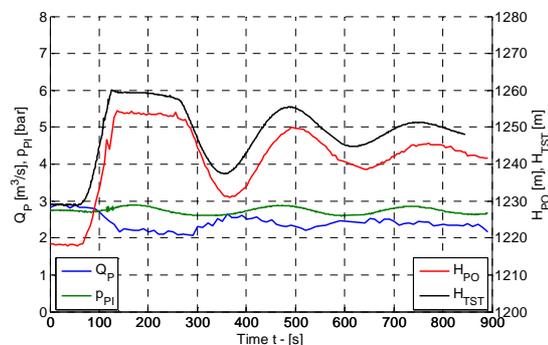


Figure 7. Shut down of one turbine while one pump and a turbine are kept in operation

Last cases presented refer to sudden load rejections of the hydraulic turbines. For one turbine load rejection while one pump operates (figure 8), the maximum pressure increase at the outlet pump section was of 1.96 bar which caused a fast response in the pump discharge decreasing from 2.4 to 1.8 m³/s together with a slight increase of the pump inlet pressure. After 7 minutes, the discharge started to increase, together with the decrease of the pump outlet pressure due to the HPP surge tank level variation. The water level increase in the HPP surge tank was equivalent to 1.2 bar, up to 1263 m elevation.

The load rejection of one turbine with two pumps in operation is presented figure 9. The pump outlet pressure had a lower increase than for the first case (1.6 bar) but the response of the pumped discharge was a fast decrease of 1.1 m³/s, for a short time (25 s), then it increased up to 4 m³/s. The inlet pump pressure had larger variation than previously, corresponding to the discharge variation. The elevation in the surge tank was similar (1263 m).

The sudden load rejection of both turbines while one pump was in operation (figure 10), was the most critical. The pressure increase at the pump outlet was 5.9 bar, accompanied by a strong decrease of the pump discharge to 1.5 m³/s. It lasted about 8 minutes before the discharge returned to a value closer to the rated one, and it induced large pressure at the pump inlet; from 2.65 up to 3.05 bar. In the inlet pressure variation, shorter periods can be noticed due the PS surge tank which compensates the mass oscillation on the pump intake circuit.

The water level in the HPP surge tank, in case of sudden load rejection of the turbines, had an oscillation period of 400 s, longer than in case of a normal stop. This is due to the faster closure of the turbines guide vane forcing a larger volume of water to enter in the surge tank. The water entered into the upper chamber; the maximum elevation was almost 1270 m, lower than the maximum surge tank level of 1276 m, and thus still in the safe operation region.

Load rejection of both turbines with one pump in operation was the most critical case, with the highest over pressures for the pumps (figure 10). For this reason, a simplified mathematical model [10] was developed to calculate the HPP surge tank elevation and the oscillation period (figure 11). In this model the hydraulic losses of the circuit, that have a strong influence over the results, were theoretically estimated, as not all data were available. In the future studies, the experimental data will be used to calibrate this mathematical model in order to simulate water hammer pressure oscillations.

The analysis of water hammer pressure waves is necessary because they were observed in all sudden load rejection cases. The pressure waves traveled from the turbines in the entire pipeline system and even through the pumps for short periods of time. The pressure waves were fast attenuated; 7-10 s. A pressure increase was also recorded at the inlet section of the PS, but still, the PS operation continued without being affected.

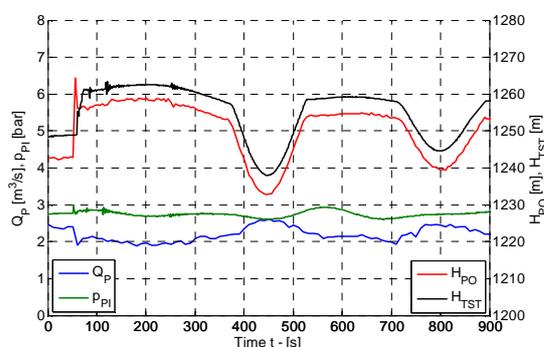


Figure 8. Load rejection of one turbine while one pump operates

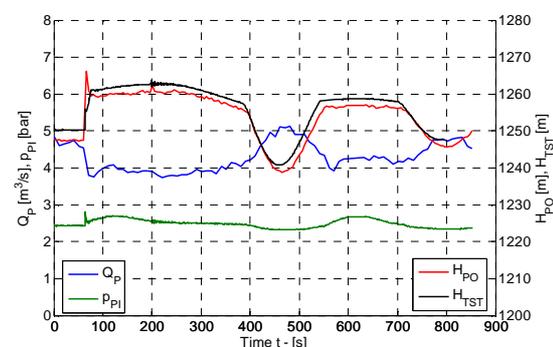


Figure 9. Load rejection of one turbine while both pump operate

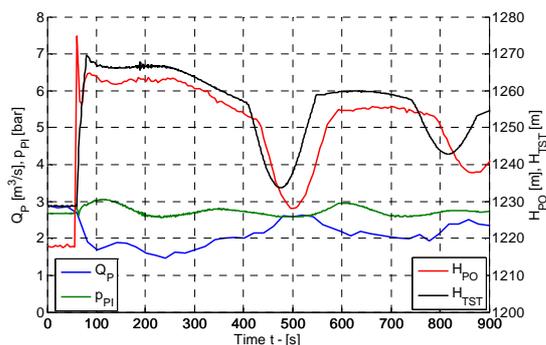


Figure 10. Load rejection of both turbines while one pump operates

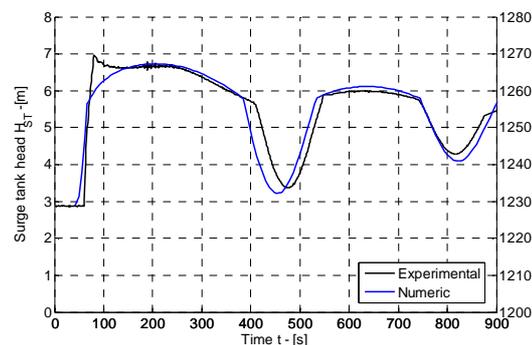


Figure 11. Surge tank level for sudden load rejection of both turbines while one pump operates (experimental and numerical)

4. Conclusions

An experimental study of a complex hydropower site, during simultaneous operation of the HPP and the PS, in case of different operations of the hydraulic machines: starts and stops of pumps, stops and sudden load rejection of turbines was presented. Several parameters of the PS (discharge, inlet and outlet pressure) and the HPP parameters (head at surge tank level and discharge) were simultaneously recorded.

The single operation of the PS was firstly investigated.

Normal stops of the turbines, while the PS was in operation, induced an over pressure of 3.6 bar at the PS outlet. The sudden load rejection had a larger impact on the outlet pressure, increasing it with 4.2 bar. Still, the outlet pressure remained in the limits of the PS capacity. The increase in the outlet pressure had a negative effect over the pumped discharge, which influenced the inlet pressure.

The pressure at the HPP surge tank was measured to determine the elevation of the water during mass oscillation phenomena in order to find if the water flows over it. In all investigated situations, the water elevation remained below the maximum height of HPP surge tank.

Turbine sudden load rejection in the HPP, caused water hammer pressure waves that travelled through the PS pipes, and even through the operating pumps being observed in the PS inlet pressure. The short period of time (7-10 sec) of this high over pressure does not seem to create the risk of changing the flow sense through the pumps.

Still, considering that the PS was not designed to operate during this fast transient pressure waves, it is important to further investigate what will be the influence of this regimes over the electrical and mechanical parameters of the pumps.

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