INFLUENCE OF THE SURGE TANK WATER INERTIA ON PUMPED STORAGE POWER PLANT TRANSIENTS IN CASE OF PUMP EMERGENCY SHUTDOWN

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ABSTRACT

This paper presents the case study observed during commissioning tests of the 185MW Avče pumped storage power plant located on the Soča River, in Slovenia, equipped with one (1) reversible Francis pump-turbine. Due to Emergency Shutdowns (ESD) in pump mode, low pressure levels appeared at the top of the penstock which could induce the unexpected opening of the air-vacuum valves of the safety gate valve and consequently air admission in the waterway. To investigate the causes of such low pressure levels, advanced transient modelling of the entire hydraulic system, including pump-turbine and air valves are performed. The validation of the model with on-site measurements are presented and these comparisons confirm the major role played by the surge tank water inertia during such cases. The positive influence of the air vacuum-valves during ESD is also demonstrated by means of numerical simulations performed "with" and "without" air-valves. Conclusions for these cases are finally presented and the counter measures taken on-site to solve the low pressure issues are listed.

KEYWORDS

Francis Pump-turbine, water hammer calculation, surge tank, air-valves.

1. INTRODUCTION

Pumped storage power plant featuring a layout with headrace tunnel, surge tank and penstock may be subjected to low pressure risk at the top of the penstock resulting from transients in pump mode operation. Indeed, water hammer caused by quick closing of the wicket gates due to a pump power failure induces negative pressure wave propagating in the penstock and consequently low pressure phase along the penstock. Besides, the risk of cavitation and water column separation, the low pressure phase may also cause the unexpected opening of air-vacuum valves located downstream the safety gate valve at the top of the penstock, producing a risk of entrapped air in the hydraulic circuit.

Such events were observed during the commissioning tests of the 185MW Avče pumped storage power plant located on the Soča River, in Slovenia, equipped with one (1) reversible Francis pump-turbine. Emergency Shutdowns (ESD) occurred during the pump start-up phase

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leading to low pressure levels at the top of the penstock, inducing the unexpected opening of the air-vacuum valves of the safety gate valve and consequently air admission in the waterway. One of these cases is presented in Fig 1, which shows the pump start-up failure followed by ESD shutdown sequence (Fig 1 Left). One can observe in the pressure measurement records at the top of penstock and penstock gate valve (Fig 1 Right), pressures dropping below atmospheric pressure. As the pressure transducers were not able to measure sub-atmospheric pressure, they featured saturation. The first simulations performed to reproduce this event, were not able to predict the negative pressure at the top of the penstock. Therefore, extensive transient analysis were carried out to understand the phenomenon roots.
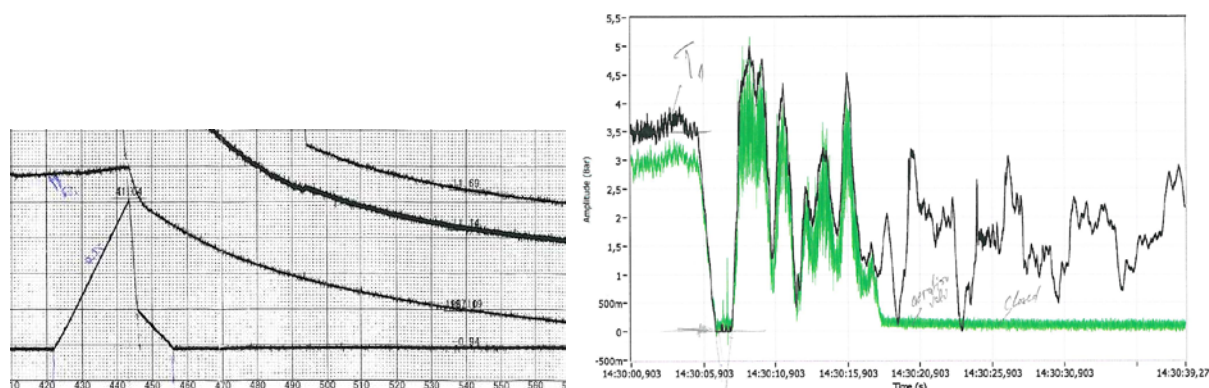

Fig 1: Left, Sequence of pump start-up failure followed by ESD (wicket gates and rotating speed) and the corresponding pressure measurements at the top of the penstock (black line) and valve gate (green line)

2. GENERAL DESCRIPTION OF AVČE PUMPED STORAGE POWER PLANT

Fig 2 presents the general layout of the 185 MW Avče pumped storage power plant comprising a headrace tunnel of 697 m long, a surge tank with upper and lower expansion chambers (Fig 3), a penstock of 1567 m long, a reversible Francis pump-turbine with a tailrace tunnel of 120 meters long. The power house consists in a vertical shaft of 18 m of diameter and 80 m deep, where the Francis pump-turbine is connected to a variable speed motor-generator of doubly fed induction machine type with speed range of -4% to +4% for pump power input adjustment. The water is pumped from the Soča River with a maximum water level of 106 masl, to the artificial upper reservoir of 2.2 Mm^3 with a maximum water level of 625 masl. Tab. 1 shows the key characteristics of the equipment installed in the power plant.

Description	Value
Maximum gross head	521 mWC
Rated discharge in turbine mode	40 m^3/s
Rated discharge in pump mode	34 m^3/s
Rated power in turbine mode	185 MW
Rated power in pump mode	180 MW
Nominal rotational speed	600 rpm
Speed range of variable speed generator	-4% to +4%
Motor-generator apparent power	200 MVA

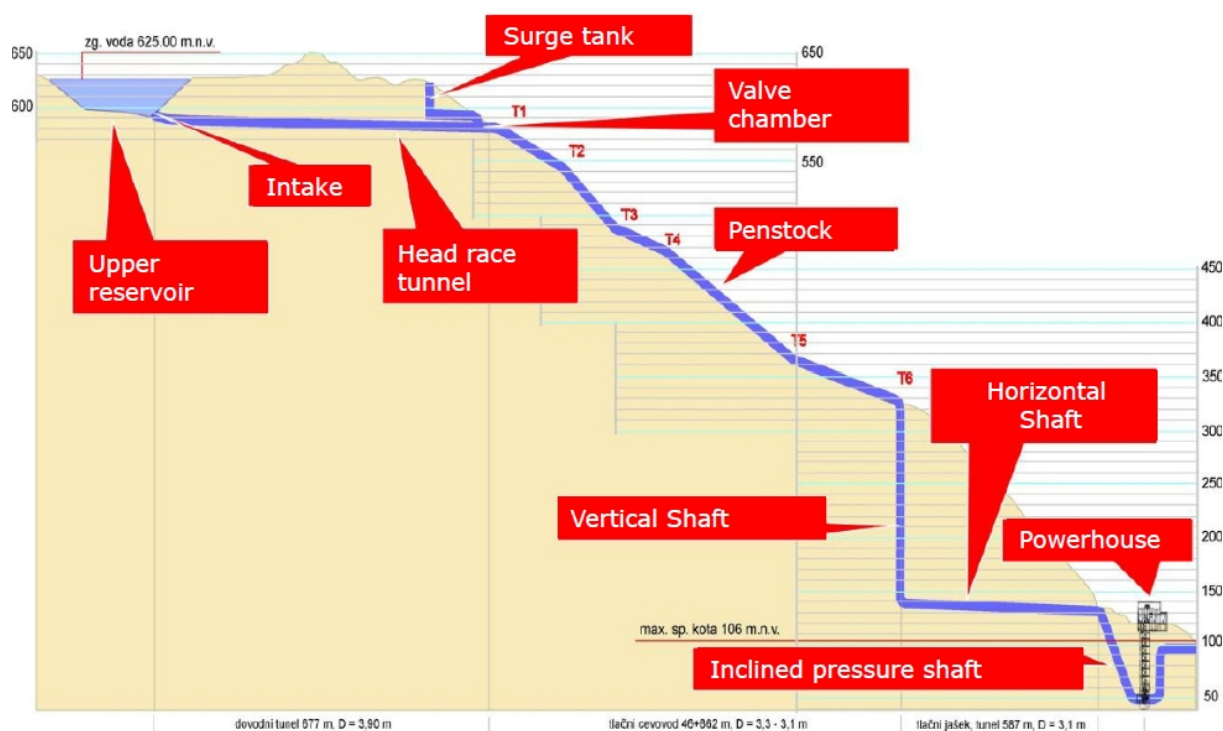*Tab. 1 Avče pumped storage power plant electromechanical characteristics.*

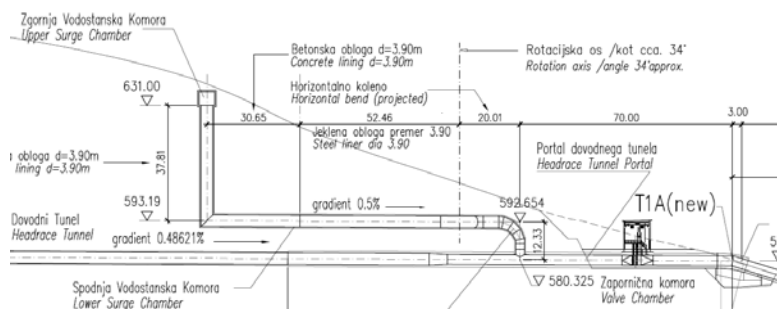*Fig 2: Avče pumped storage power plant hydraulic layout*

Fig 3: Surge tank layout and safety gate valve

3. MODELLING OF AVČE PUMPED STORAGE POWER PLANT

The Avče pumped storage power plant was modelled using the simulation software SIMSEN developed by EPFL [1]. The model considered the upper and lower reservoirs with constant water levels, the headrace tunnel, the surge tank with expansion chambers, the penstock, the reversible Francis pump-turbine modelled by its actual 4-quadrants characteristics as well as its total rotating inertia, and the tailrace tunnel. The simulation model enables to take into account the water hammer, mass oscillations, and pump-turbine 4 quadrants operation with the resulting instabilities due to the well-known S-shape characteristic.

The lower expansion chamber of the surge tank consists in one horizontal pipe of 3.9 meters of diameter and 107 meters long and it is always filled with water at standstill and normal operation of the unit. During transients caused by pump emergency shutdown, this chamber acts as a pipe. Indeed, the water in the surge tank has to be accelerated from standstill to a flow rate corresponding approximately to the pump discharge of 34 m^3/s. The flow accelerating time is increased by the rather long length and small diameter of the lower surge chamber inducing high water inertia. Therefore, for the modelling of the surge tank, the inertia of the water inside the surge tank flowing through the pipe cross section has to be

considered by including a hydraulic inductance. It must be pointed out that model of typical surge tanks considers the storage effect of the surge tank and the inlet/outlet head losses only which are modelled in SIMSEN software through electrical analogy respectively by capacitance and resistance. Fig 4 presents the modelling of surge tank with additional inductance to account for surge tank water inertia. The head in the tunnel H_{SS} is then given by the set of two differential equations:

$$\begin{cases} H_{SS} = h_c + R_d \cdot Q_c + L_{SS} \cdot \dfrac{dQ_c}{dt} \\ C_{SS} \cdot \dfrac{dh_c}{dt} = Q_c \end{cases} \tag{1}$$

Where:

$$R_d = \frac{K_d}{2 \cdot g \cdot A_{ref}{}^2} |Q_c| \qquad L_{SS} = \int_{z_{in}}^{h_c} \frac{dx}{g \cdot A(x)} = \frac{l_{equ}}{g \cdot A_{mean}} \qquad C_{SS} = A(z) \tag{2}$$

With x the curvilinear abscissa along the surge tank between inlet and free surface, and l_{equ} and A_{mean} the total length respectively the mean cross section area of an "equivalent pipe" modeling the surge tank water inertia.
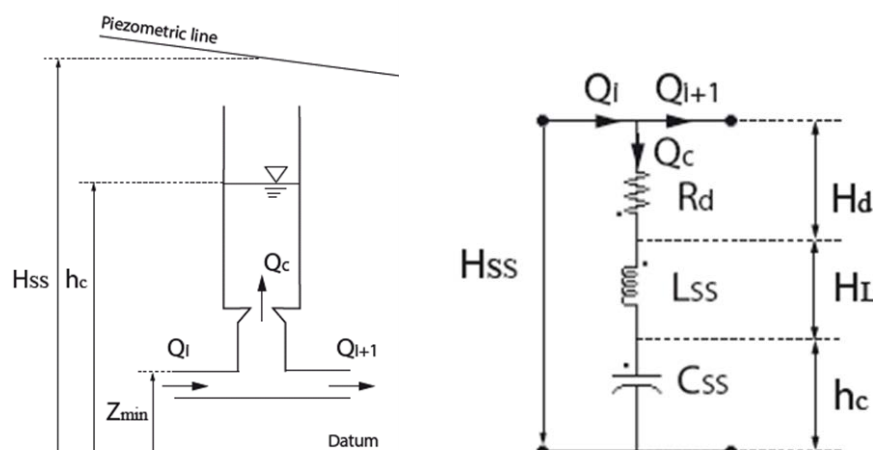

Fig 4: Modelling of surge tank based on electrical analogy with additional hydraulic inductance to account for water inertia.

The SIMSEN simulation model of the Avče pumped storage power plant was validated by comparison between on-site measurements and simulation results in case of turbine emergency shutdown and pump emergency shutdown as presented in Fig 5 and Fig 6 respectively. The good agreement obtained between measurements and simulation results confirms the adequate modelling of hydraulic system and pump-turbine transient in both turbine and pumping mode.

4. LOW PRESSURE EVENT DURING PUMP START-UP AND ESD

Fig 7 presents the simulation results of the sequence of pump start-up failure followed by emergency shutdown (see also Fig 1) which occurred at a low upper reservoir level. The comparison of simulation results of the pressure at the top of the penstock (location T1A) obtained "with" and "without" inertia effects (Fig 7 right) shows significant difference in the prediction of the minimum pressure induced by the pump power failure. In particular, one can observe that the pressure drops very fast when considering the surge tank inertia which causes a delayed reaction of the surge tank to a very fast penstock discharge change induced by the pump tripping. By comparing the on-site measurements at the location T1A (top of penstock) and the simulation results (Fig 8) one can observe a good agreement in terms of pressure and

mass oscillation in the surge tank, therefore confirming the appropriate modelling of the surge tank when water inertia is considered.

It must be highlighted that the first results obtained by using a model of equivalent pipe (to represent the surge tank inertia) with a length equal to the total length of the surge tank, did not match very well with the experimental results. A calibration was necessary and it was found that with an increase of about 30% of the pipe length, the best matching with measurements was obtained. The origin of this increase may result from additional inertia of flow at low Reynolds as the water in the surge tank is initially at stand still, see Wylie and Streeter, [2].

Additional comparison between measurements and simulation results in case of pump ESD from steady state conditions at higher upstream water level as shown in Fig 9 confirms also the good agreement when surge tank water inertia is considered.
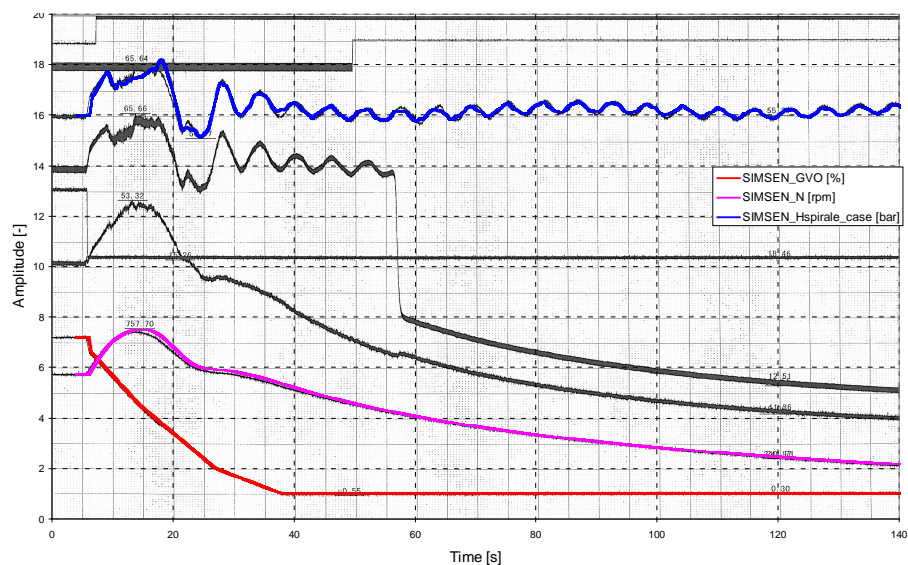

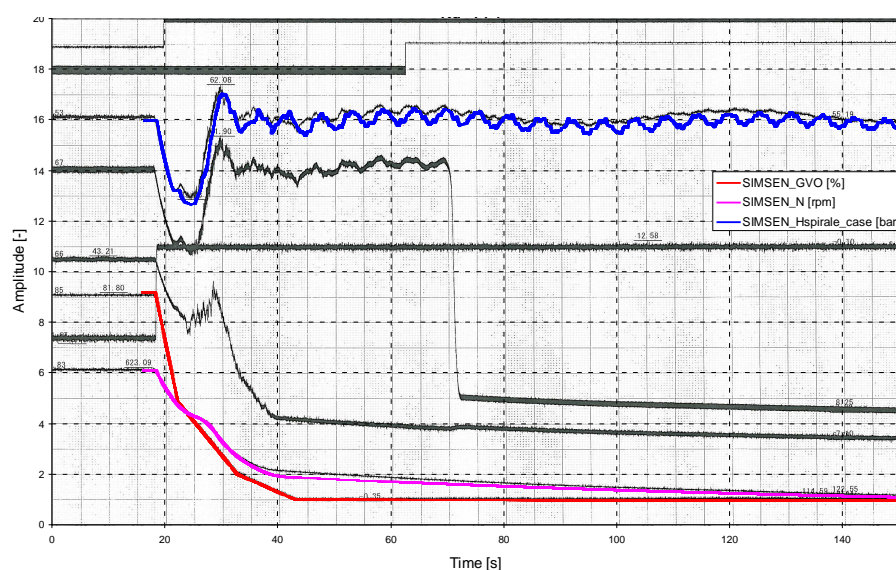*Fig 5: Comparison of simulation results and on-site measurements in case of turbine ESD.*

Fig 6: Comparison of simulation results and on-site measurements in case of pump ESD.
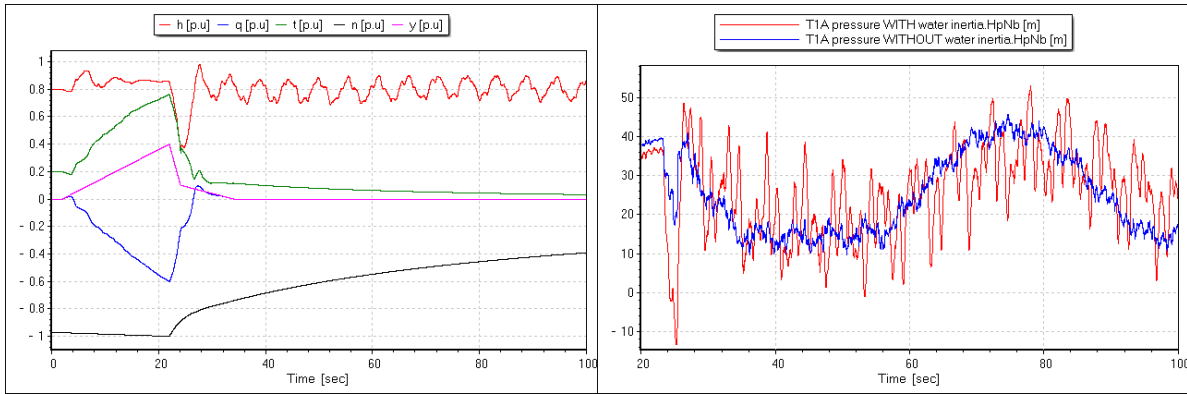
Fig 7 Simulation results of pump-turbine transient in case of pump start-up failure followed by emergency shutdown, (left) and corresponding simulated pressure at the top of penstock (location T1A) obtained "with" and "without" surge tank inertia effect (right).
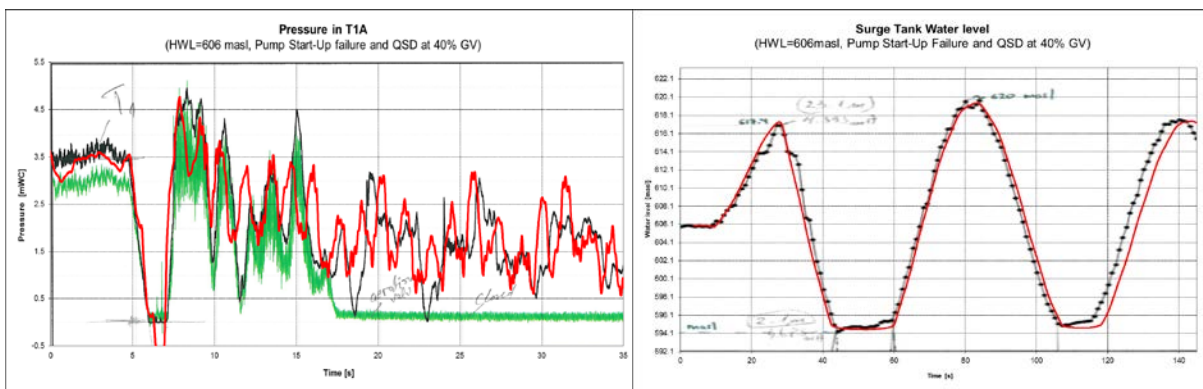

Fig 8: Comparison between simulation results with surge tank water inertia (red line) and on-site measurements resulting from pump-turbine transient of pump start-up and emergency shutdown recorded on November 5, 2009, for time evolution of the pressure at the top of the penstock (left) and surge tank water level (right).
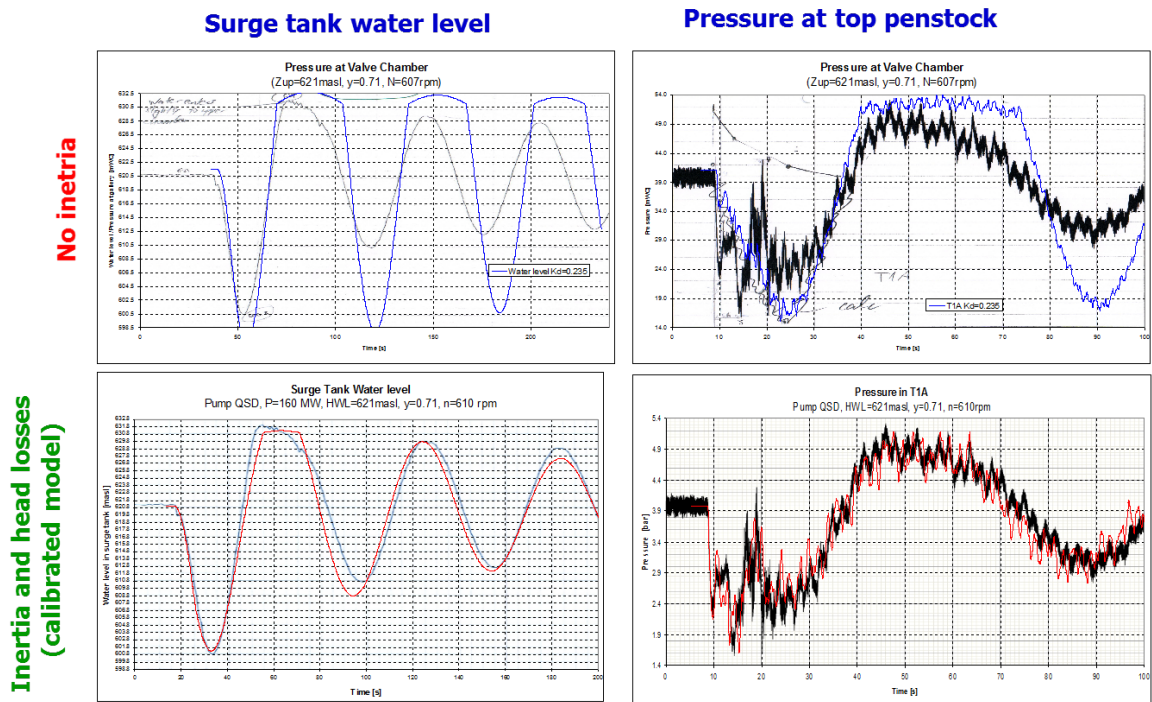

Fig 9: Comparison between simulation results "with" and "without" surge tank water inertia and on-site measurements resulting from pump ESD at high water level.

5. AIR VALVE INFLUENCE

The low pressure resulting from transients due to pump ESD may lead to unexpected opening of the air-valves located downstream of the safety gate valve at the top of the penstock (see Fig 3), and this may induce air admission in the hydraulic circuit. The case to study was caused by an incorrect functioning of servomotor during normal stop which led to a pump ESD (Fig 10 left). In order to reproduce the event by simulation, the modelling of air-valves according to Wylie and Streeter [2] were included. The model is based on the following hypothesis: perfect gas, isentropic flow, isothermal transformation, instantaneous opening/closing of air-valves, small volume of air compared to the pipe volume, and air remaining in the vicinity of the air valve from where it can be expelled.

Fig 10 shows the comparison between simulation results "with" and "without" air-valve modeling and on-site measurements for the pressure at the top of the penstock (T1A). One can observe that the air-valve model enables to reproduce the overpressure resulting from the compression of the air admitted by the air-valves. Fig 11 presents comparison between simulation results with and without air-valve model leading to the following conclusions i) as expected the air-valve enables to restricts minimum value of the low pressure at penstock top, see Fig 11 left, which would prevent from cavitation and water column separation, ii) when the air is expelled, due to lower exit cross section than intake cross section, the air is compressed, and induces local pressure increase adequately reproduced with perfect gas assumption. This air compression is transmitted all along the penstock and it is also visible on the spiral case pressure, see Fig 11 right, which was confirmed by on-site measurements.
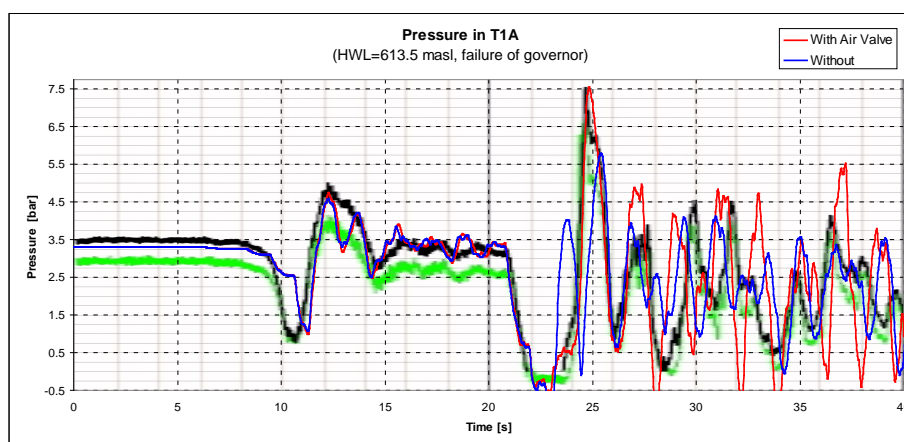

Fig 10: Comparison between simulation results with and without air-valve modelling and on-site measurements resulting from pump ESD at intermediate water level.
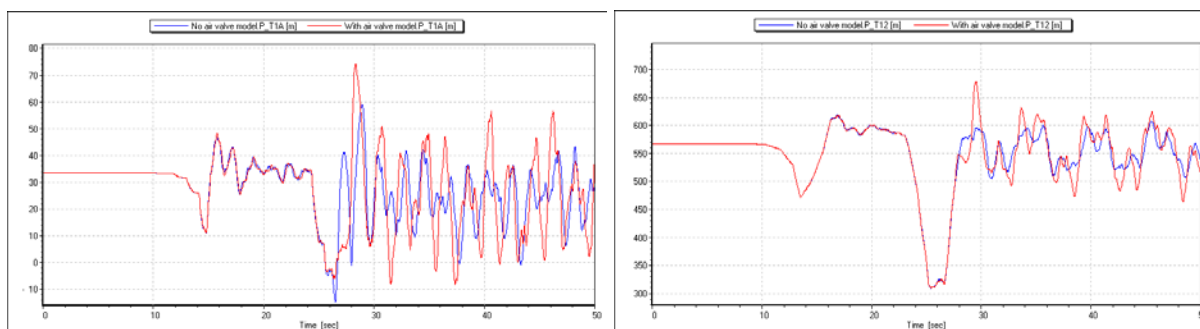

Fig 11: Comparison between simulation results with and without air valve modelling for the time evolution at the top of the penstock (left) and pump-turbine spiral case pressure (right).

6. CONCLUSION

This paper presents the transient issues caused by emergency shutdowns in pump mode during commissioning tests at Avče PSPP leading to low pressure levels at the top of the penstock, which may additionally cause the opening of the air-vacuum valves usually placed at elevated positions above the safety gate valves. The good agreement obtained between simulation results and on-site measurements have shown the decisive importance of taking into account the surge tank water inertia to adequately predict the minimum pressure obtained at the top of the penstock and thus identifying possible sub-atmospheric pressure.

Simulation results obtained with air-valves also shown the ability of such devices to restrict pressure drops at the top of penstock by air-admission limiting the pressure to few meters below atmospheric pressure if the air-valves are appropriately sized. Overpressure due to air compression when it is expelled was also shown.

We shall mention that the low pressure issues encountered during pump emergency shutdowns at Avče PSPP have been solved with several counter measures: (i) guide vane closing law modification, (ii) air-valves elevation reduction and (iii) addition of a venting pipe in the surge tank in order to break the inertia effect in the horizontal low chamber, see Rodic et al. [3].

7. ACKNOWLEDGEMENTS

8. REFERENCES

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[3]   Rodic, P., Mlacnik, J. Ivetic, M., Rejec, A., Komel, M., The hydraulic model study of the improvement of the surge tank, at Avce pumped storage power plant with aeration pipe, Proc. of Hydro2013 Conference, Innsbruck 7-9 October 2013, paper 08.07.

9. NOMENCLATURE

H_{ss}	(m)	head at surge tank connection			
h_c	(m)	surge tank water level			
R_d	(s/m^2)	hydraulic resistance	Q_c	(m^3/s)	discharge in surge tank
L_{ss}	(s^2/m^2)	hydraulic inductance	C_{ss}	(m^2)	capacitance
K_d	(-)	throttle loss coeff.	A_{ref}	(m^2)	throttle ref. cross section
H_d	(m)	head at the throttle	H_L	(m)	head due to water inertia