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Practical experiences with water hammer control in Slovenian hydropower plants

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Abstract. Water hammer control for new and refurbished hydropower plants in Slovenia is the main topic of the proceeding paper. General design approaches and water hammer control strategies are presented. A general outline of topographical and hydrological conditions that govern the construction of hydropower schemes in Slovenia is also included. Presented case studies cover the last two decades of hydropower plant development in Slovenia.

1. Introduction

Together with forests, water is the only true natural resource in abundant supply in Slovenia. With an annual quantity of 17,000 m^3 of water per capita the country is ranked third in Europe, after Switzerland and Norway [1]. Two water regions divide the country; the Danube River (Black sea) and the Adriatic seawater region. There are three mayor river catchment areas: Drava, Sava and Soča. They are characterized by a combination of nival and nival-pluvial regime with the gross hydropower potential estimated at 19,440 GWh/year. So far 45 % of the total technically available potential (4,115 GWh/year) has been exploited, hydropower plants generating approximately 30 % of the total installed capacity.

Conditions for construction of high head hydro power schemes or conventional reservoirs with high dams are not favourable. Most of the corresponding potential sites are located in environmental sensitive areas or sites where construction would not be economically feasible.

Electricity generation in Slovenia using hydropower started at the end of nineteenth century with the first turbine installed in Škofja Loka [2]. Construction of the Završnica hydropower plant in 1914 and later Fala hydropower plant in 1918 marked a turning point in terms of electrification of the country.

Mayor developments were made after 1945 with the return of Primorska region back to Slovenia with its hydropower plants on the Soča River. In the 1960s, to cover basic demands for electricity, the construction of hydropower plants on the Sava and Drava River began and continued through the 1970s. Post-independence period saw interconnection of the Slovenian power grid to the common European network. Construction of the chain on the lower Sava River and the start of refurbishment of existing facilities began soon after that.

Regarding the river basins, the Sava River basin is the largest of them and presents more than 50 % of the country total area but it is the least utilized in terms of hydropower with total installed capacity of 230 MW. Completion of the chain on the lower Sava River is underway and start of procedure for design of the middle Sava River chain where 10 hydro power plants are foreseen.

The Drava River basin is the most important and also the most developed with installed capacity of 600 MW. A comprehensive refurbishment programme has been completed with replacement of all worn out electromechanical equipment. Drava is a border river and the operating regime of the chain must be co-ordinated with operation of the chain on the Austrian side for a daily run-of-river storage regime.

The Soča River basin is ideal for hydropower production due to its high annual rainfall in the southern Alpine mountains. Three mayor hydropower plants have a total capacity of 142 MW and a pump-storage plant Avče completes the Soča river basin utilization with additional 180 MW capacity.

There is also the Mura River, but at present it is not being exploited for hydroelectric production due to environmental restrictions. The river has a nival regime of discharge as the waters are fed from the central Alpine mountains and maximum annual discharges occur at late spring. This is favourable compared with other catchment areas which lack water during the summer. The possible foreseen installed capacity is 158 MW based on the principle of flow-of-the river, which has less influence on the natural habitats [1].

2. Hydraulic transients

General issues related to hydraulic transients have already been presented in the past [3, 4]. Specific transient issues relating to Francis and Kaplan turbines which will be covered in this paper are:

- relatively short inlet and outlet conduits and the usage of rigid column water hammer theory,
- check for water column separation under the Kaplan turbine head cover,
- installation of a surge tank for a low-head Kaplan turbine and medium-head Francis turbine developments,
- installation of pressure regulation valve in a channel type Kaplan turbine development.

Modelling will be performed using commercial computer packages [5, 6]. The EPFL SIMSEN commercial software package [5] is based on modular structure, composed of objects, where each object represents a specific network element. Hydraulic elements are modelled as RLC electrical circuits according to the impedance method [7]. Momentum and mass conservation equations provide the basis for an equivalent electrical circuit modelling and corresponding propagation of pressure waves in the pipeline (elastic water column)

For relatively short inlet and outlet conduits (length of the conduit is of the same order as the cross-sectional dimensions) and complex cross-sectional shapes the rigid column water hammer theory is used in MISI TRANK software package [6]. Rigid water column is described by the one-dimensional Bernoulli equation for unsteady flow which is solved simultaneously with the dynamic equations of the turbine unit rotating masses, taking into account the turbine characteristics. In addition to unit discharge and unit torque, the unit axial hydraulic thrust characteristics (F_{a11}) are implemented in the turbine model.

2.1. *Water column separation and axial hydraulic thrust*

Transient regimes must be controlled in such a way that the operation of the turbine is safe and reliable. One of the most severe transient regimes is the emergency shut-down triggered by the over-speed device, which is set to operate at an excessive speed rise.

Particular attention should be made to reverse water hammer that can occur in hydropower plants with long outlet conduits. Water column separation can occur under the turbine head cover and the draft tube inlet during closing of the Kaplan turbine guide vanes and runner blades. Two approaches are used in the estimation of potential danger of full column separation in Kaplan type turbines [8].

Turbine head cover pressure criterion. On the basis of model measurements the absolute pressure under the turbine head cover is calculated. Pressure is measured at several locations in the space between the guide vanes and runner blades. The pressure under the turbine head cover is then calculated using measured axial hydraulic thrust characteristics. The computed absolute pressure should be larger than the vapor pressure $p_a > p_{vp}$.

Axial hydraulic thrust criterion. The potential danger of full column separation and Kaplan turbine unit lifting during transient events are estimated using the measured model axial hydraulic thrust characteristics. Full column separation under the head cover and subsequent cavity collapse induces large axial hydraulic thrust acting upwards. If the absolute value of the hydraulic thrust acting upwards

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is greater than the total weight of the rotating parts of the unit, then the unit may be lifted from the thrust bearings causing structural damage. The following expression is valid:

$$\left|F^-{}_{a,\max}\right| = \min\left\{\left|F^-{}_{ad}\right|, W_u\right\} \tag{1}$$

in which F^-_{ad} = damaging axial hydraulic thrust acting upwards and W_u = total weight of the rotating parts of the unit.

The damaging axial hydraulic thrust is calculated by the following equation in which the full water column separation under the head cover is assumed to occur:

$$F^-{}_{ad} = -\rho g \frac{\pi D^2}{4}\left(1-\frac{d^2}{D^2}\right)\left(10-\frac{Z_{twl}}{900}\right)+\rho g \frac{\pi D^2}{4}\left(H_s-\Delta H_i\right) \tag{2}$$

in which ρ = mass density, g = gravitational acceleration, D = runner diameter, d = turbine shaft diameter, Z_{twl} = tail water level, H_s = suction head and ΔH_i = dynamic head.

The dynamic head is calculated with the following equation:

$$\Delta H_i = \frac{Q_{sc} G_d}{g t_{sc}} \tag{3}$$

in which Q_{sc} = discharge at the moment of assumed water column separation, G_d = geometric characteristics of the draft tube and t_{sc} = closing time from discharge Q_{sc} to discharge Q = 0 m^3/s. Installation of air valves has limited influence on the application of the above criterion and cannot prevent damaging reverse water hammer.

3. Case study 1: Zlatoličje Hydropower Plant

Eight run-of-the river hydropower plants form a chain on the Slovenian part of the Drava River extending from the Austrian to the Croatian border. During the last twenty years seven HPP have been fully refurbished and upgraded. These include Fala HPP (1991), Dravograd HPP (1997), Mariborski otok HPP (1997), Vuzenica HPP (1997), Ožbalt HPP (2004), Vuhred HPP (2004) and Zlatoličje HPP (2012). A total of twenty Kaplan units were replaced by new runner design with larger diameters (+5 %) increasing the discharge capacity in the existing flow-passages by about 25-30 %.

Zlatoličje HPP is designed as a channel-type power plant. It is the largest Kaplan type turbine in Slovenia and generates more than a fifth of all the electric power generated by its parent company DEM. Constructed in 1966 the two units utilize 33 m head at a threshold capacity of 160 MW. The plant is connected to 17.2 km long trapezoidal profile inlet cannel, see Figure 1. The outlet channel is 6.2 km long and joins the Drava River at the Ptuj Lake, the largest artificial lake in Slovenia.

Figure 1. Zlatoličje HPP (foto www.dem.si).

Each of the two units is equipped with a pressure regulating valve (PRV) comprised of five vertical vanes connected via rod to a servomotor and controlled by the turbine governor. During transient operating regime the PRV is designed to completely attenuate free surface waves in the inlet and outlet channels. The continuous measurements of the channel water levels at the turbine inlet and outlet have indicated that water level oscillations in the channels are small and within the prescribed limits during transient regimes.

Emergency shut-down of the Kaplan turbine from 75 MW output is discussed [9]. The turbine is disconnected from the electrical grid followed by the complete closure of the wicket gates while the runner blades open to their fully open position (Figure 2(a)). The PRV blades first open to about 90 % opening synchronously with the wicket gate closure and then start to close at a very slow rate to its fully closed position (Figure 2(a)). The PRV linear full-stroke closing time is $t_{c,PRV}$ = 1,200 s. The continuous measurement of the channel water levels at the turbine inlet and outlet indicates that water level oscillations in the open channel are small and within the prescribed limits during the transient event. Figure 2(b) shows measured head water level variations (Z_{HWL}) during the period of the turbine closure.

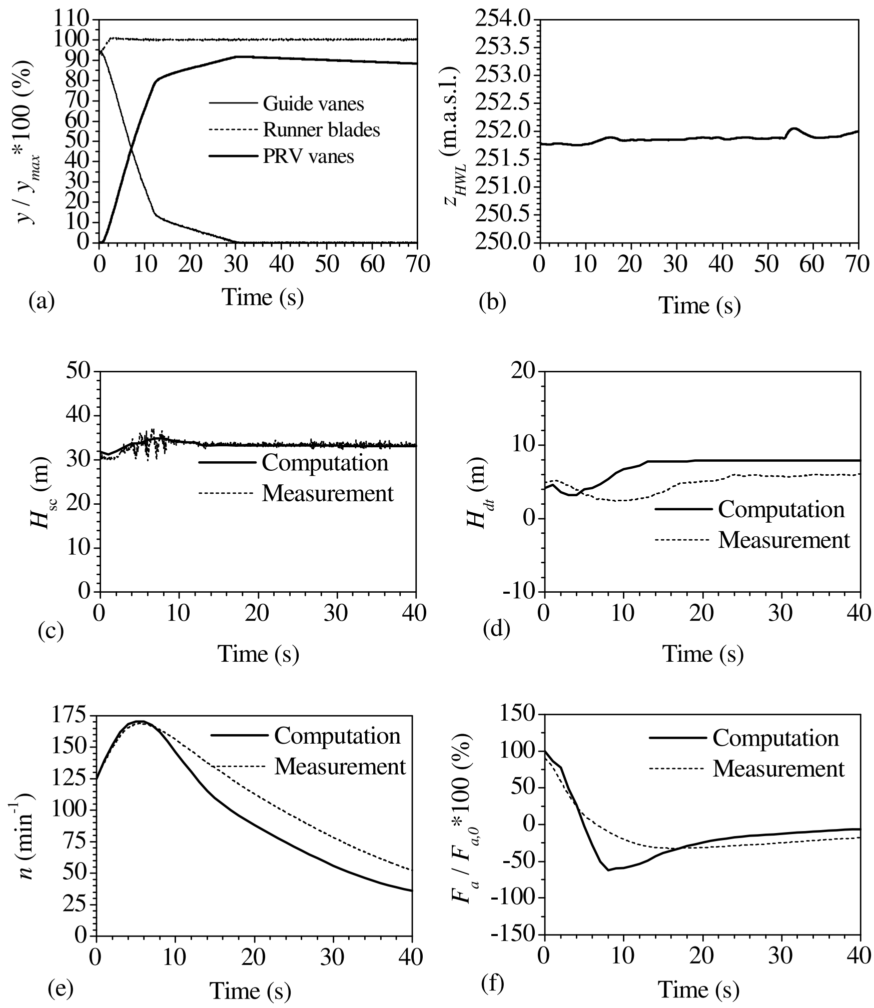


Figure 2. Emergency shut-down of Kaplan unit in Zlatoličje HPP (P = 75 MW): Guide vane, runner blade and PRV servomotor strokes (a), head water level at the turbine inlet (b), scroll case head (c) draft tube head (d), unit rotational speed (e) and axial hydraulic thrust (f).

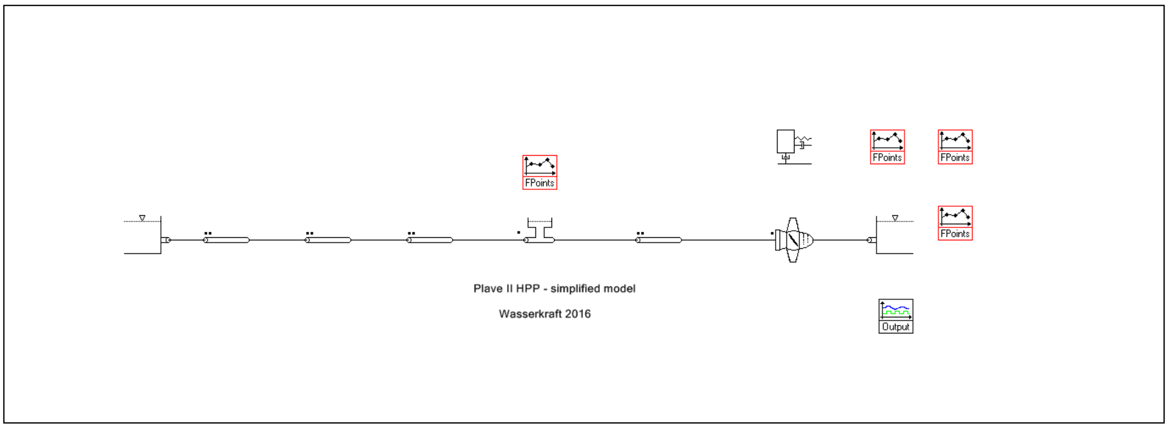
During this period of the transient operating regime the pressure regulating valve completely attenuates free surface waves in the inlet channel. This is practically true for the oscillations in the outlet channel too (Figure 2(d)). Therefore, the constant water levels at the turbine inlet and the turbine outlet are assumed in water hammer calculations. Figures 2(c-f) show results of rigid column water hammer analysis for the considered emergency shut-down of the unit. The agreement between the computed and measured maximum rotational speed (n) 169 min^{-1} and 171 min^{-1}, respectively, is good. The computed maximum momentary scroll case pressure head (H_{sc}) of 35 m practically coincides with the averaged measured one (Figure 2(c)); there is a reasonable agreement between the calculated and measured draft tube pressure head too (Figure 2(d)). The maximum scroll case pressure head and the maximum speed rise are within the prescribed limits. The calculated and the measured maximum momentary negative axial hydraulic thrusts (absolute values) of 3500 kN and 1600 kN, respectively, are less than the permissible thrust $|F^{-}_{a,max}|$ = 5370 kN (Figure 2(f); $F_{a,0}$ = 5680 kN). There is a large discrepancy between the magnitudes of the negative axial hydraulic thrust. The maximum calculated axial hydraulic thrust is based on the model measurements. It is difficult to measure hydraulic quantities in the model at smaller wicket gates openings (large uncertainties), in particular, at an increased rotational speed of the turbine. There is a large uncertainty in the measured axial hydraulic force on the prototype too. However, the general trace of calculated and measured axial hydraulic thrust is similar.

4. Case study 2: Plave II Hydropower Plant

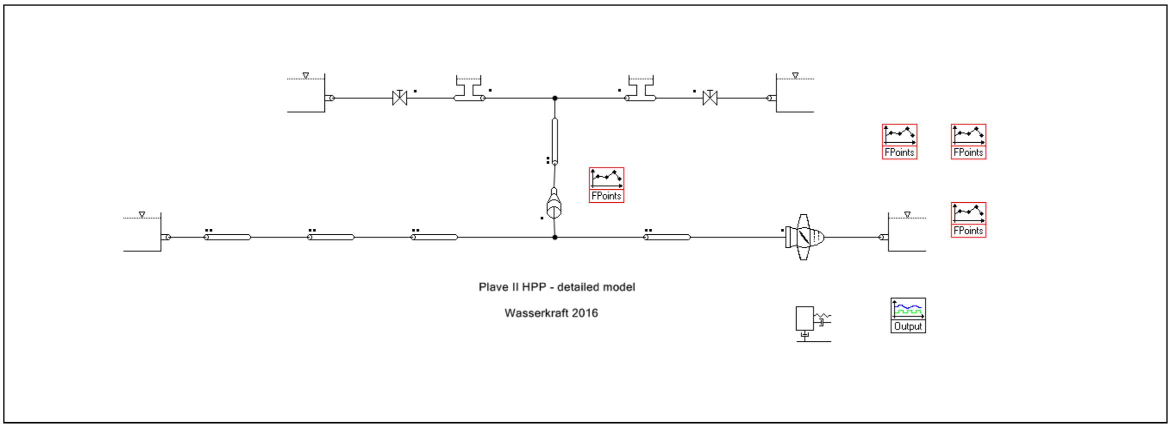
The design of Plave II HPP on the Soča river basin was based on the exploiting the available hydro potential and infrastructure of the existing Plave I HPP built prior to WWII. While the Plave I HPP uses a free surface water underground diversion channel, Plave II HPP has a low pressure diversion tunnel connected at the end to an expansion chamber. The tunnel is lined with prefabricated concrete elements. Complete length of the tunnel is 6.1 km with equivalent diameter of 6.3 m and runs parallel to the Plave I HPP channel. TBM method for tunnel construction was used for the first time in Slovenia. The expansion chamber (tunnel) connects the low pressure tunnel to a double-cylinder surge tank, each of 26 m diameter. The low pressure tunnel continues to the power station as a penstock (length 186 m; equivalent diameter 5.8 m). A vertical Kaplan turbine of 20.5 MW capacity is installed in the power house.

Due to long tunnel with surge tank and relatively long penstock elastic column water hammer model has been used [5]. A simplified and detailed model of the surge tank was analysed. Figure 3(a) presents the basic or simplified model of the flow-passage system. Two surge tanks are replaced in the model with a single equivalent surge tank of 37 m diameter. The design of the surge tank and orifice was tested in a hydraulic research laboratory. Figure 3(b) presents a more detailed model of the flow-passage system. Two surge tanks are included and also the connecting pipe from the low pressure tunnel.

As seen from the full load emergency shut-down results presented in Figure 4 [10] the main difference between the two models is in the result for the penstock pressure; 38 m for the simplified model and 44 m for the detailed model. The difference can be attributed to the inertia of the water column in the connecting pipe between the low pressure tunnel and the penstock. A minor difference is present for the rotational speed n (219 min^{-1} vs. 225 min^{-1}), while there is no difference in the maximum surge tank water level H_{st} (109.6 m.a.s.l.). Detailed model was used in final transient analysis.



(a)



(b)

Figure 3. Plave II HPP computational model: Simplified surge tank model (a), detailed (actual) surge tank model (b).

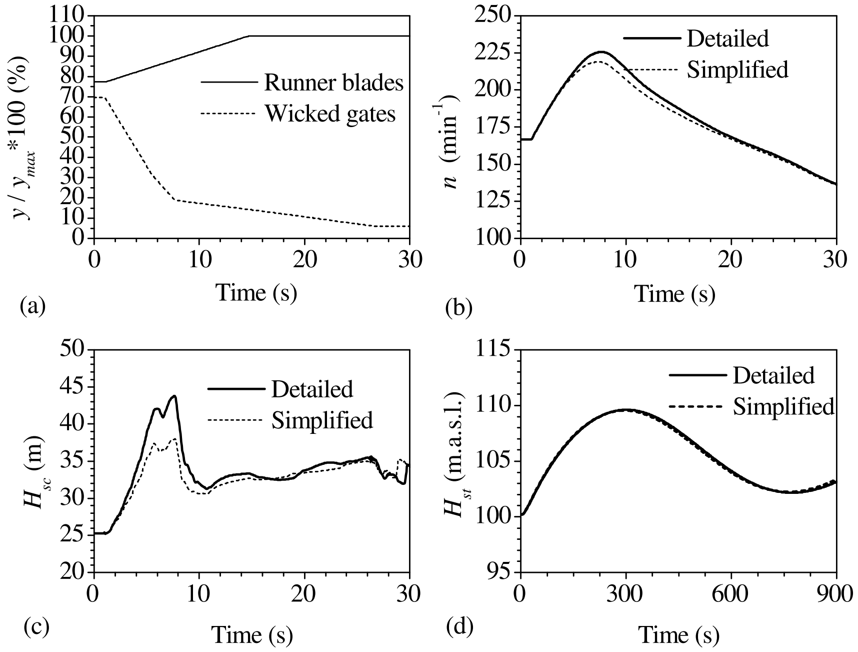


Figure 4. Emergency shut-down of Kaplan unit in Plave II HPP (P = 20.5 MW): Guide vane and runner blade servomotor strokes (a), unit rotational speed of Kaplan unit (b), penstock pressure (c) and surge tank water level (d).

5. Case study 3: Moste Hydropower Plant

Moste was the first hydro power plant to begin operation on the Sava River in 1952. The concrete arch-gravity dam with its 60 m height is the highest dam in Slovenia. Moste HPP was designed as a storage power plant for the production of peak energy. At first three vertical shaft Francis units were installed in the Moste HPP powerhouse with the total discharge capacity of 28.5 m^3/s. The system was supplemented in 1977 with the installation of a fourth unit to operate in turbine and pump mode and through connection with the penstock of Završnica HPP. The system was designed so as to allow the pumping of the water from Sava River into the higher-lying Završnica storage reservoir during surplus energy production which, unfortunately, due to the pollution of the Sava River, ceased to operate. Because of this the unit 4 was reconstructed to operate in turbine operational mode only.

Due to the severe landslide problems and need for modernization it was decided to replace the three main units with two larger units. The space of one unit was abandoned and used for construction of a reinforced powerhouse as to decrease the unfavorable effects of the powerhouse structure deformation - see Figure 5.

Various operating regimes were performed during commissioning tests of new units including turbine start-up, load acceptance, sudden load rejection, emergency shut-down and closure of one or two turbine inlet valves under various flow conditions. The resulting water hammer was controlled by appropriate adjustment of wicket gate and turbine inlet valve closing. The computed and measured results are compared for simultaneous sudden load rejection of two turbines [11].

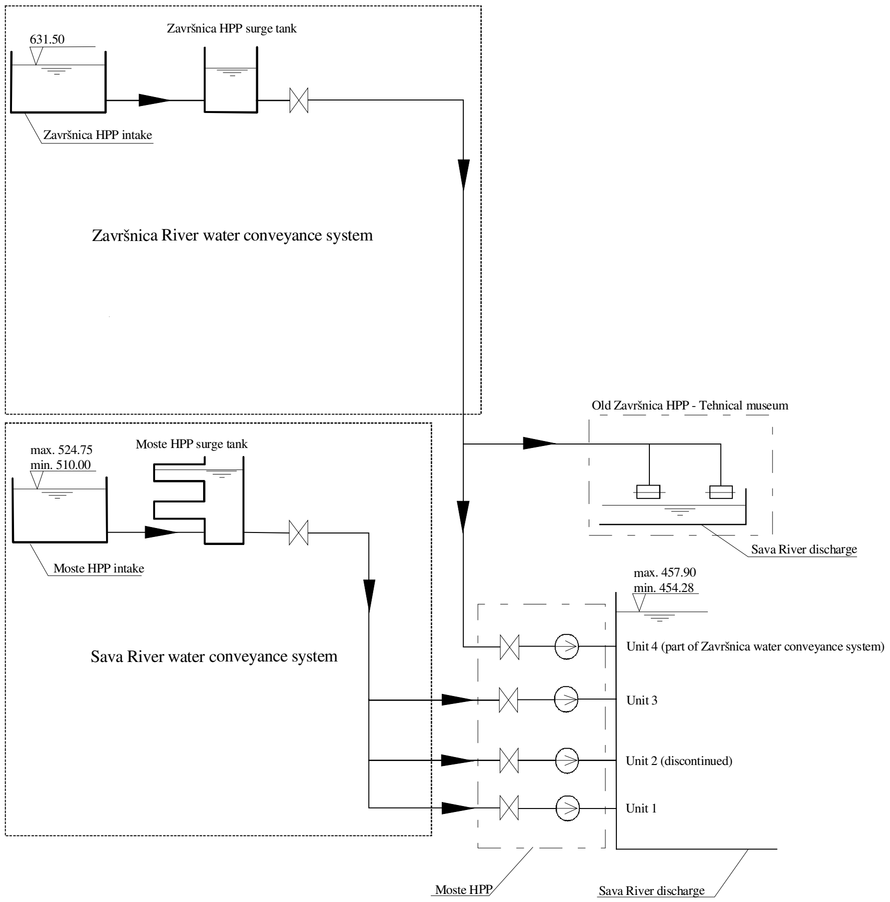


Figure 5. Moste HPP water conveyance systems.

The units are operating at output P = 6.7 MW each (units 1 and 3, unit 4 is at standstill – see Figure 5). In the presented operating regime, after disconnection from the electrical grid, the wicket gates do not fully close. The turbine regulator controls the wicket gates opening at speed-no-load conditions.

Results are presented in Figure 6(a)-(d). The computed maximum head (H_{sc}) of 87.3 m is higher than the measured one 81.5 m. As it can be seen from the results, the maximum computed head exhibits a peak value at the point of wicket gates cushioning position, whereas in measured results no such peak value occurs. There is a good agreement between the results of computation and measurements in the initial phase of the wicket gates closing event. The computed maximum turbine rotational speed n = 711.5 min^{-1} is higher than the measured turbine rotational speed n = 696.2 min^{-1}. Longer observation of penstock pressure shows the effect of surge tank on pressure attenuation (Figure 6(d)).

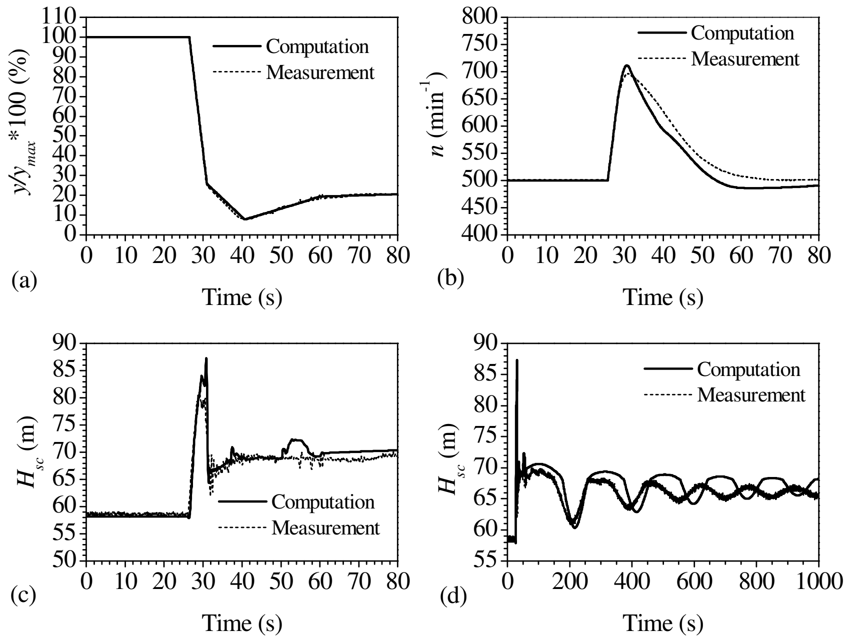


Figure 6. Sudden load rejection of two Francis units in Moste HPP (P = 6.7 MW each): Guide vane servomotor stroke (a), rotational speed (b), penstock pressure head (c), and penstock pressure head – longer time interval (d).

6. Case study 4: Brežice Hydropower Plant

Construction of the lower Sava River reach chain is currently one of the largest infrastructure projects in Slovenia. Brežice HPP is the 5th in a chain of 6 planned run-of-the river hydropower plants. When completed the 6 hydropower plants will account for 20 % of hydropower plan production in Slovenia. Three Kaplan units with total installed discharge of 500 m^3/s and rated power of 15.3 MW each will have a planned yearly production of 161 GWh. Full automatic remote control of operation is foreseen. Major additional landscaping and municipal engineering work was performed in order to provide flood protection, compensate for lost habitat and make way for possible future tourist development – see Figure 7.

Emergency shut-down from 21 MW output is observed. Figure 8 shows results of rigid water hammer analysis for the considered emergency shut-down of the unit.

Figure 7. Brežice HPP (foto www.he-ss.si).

The agreement between the calculated and measured maximum unit rotational speed of 146 min^{-1} and 145 min^{-1}, respectively, (Figure 8(b)), is very good. The same can be said for the maximum scroll case head (H_{sc}); the calculated value is 18.1 m and the measured one is 18.0 m (Figure 8(c)). The maximum scroll case head and the maximum speed rise are within the prescribed limits. The calculated and the measured extreme values of axial hydraulic thrusts (F_a) agree well; calculated extreme values are 1843 kN and -550 kN (maximum acting downwards and minimum acting upwards respectively) and measured values are 2215 kN and -752 kN, respectively. The general trace of calculated and measured axial hydraulic thrusts is similar.

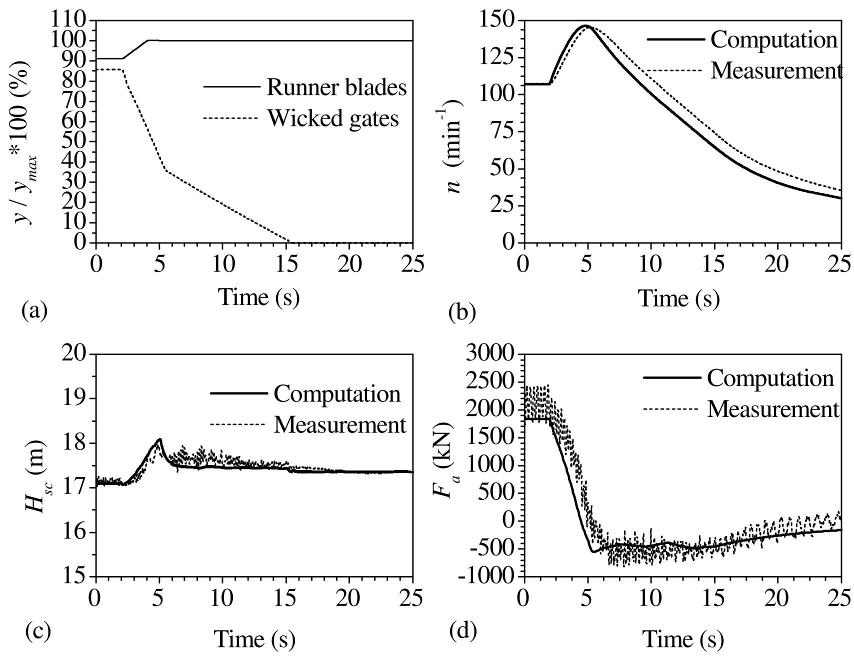


Figure 8. Emergency shut-down of Kaplan unit in Brežice HPP (P = 21 MW): Guide vane and runner blade servomotor strokes (a), rotational speed (b), scroll case head (c) and axial hydraulic thrust (d).

7. Conclusions

This paper presents practical experiences with water hammer control in a number of Slovenian hydropower plants. Case studies cover the last two decades of hydropower plant development on all three mayor river basins including Drava, Sava and Soča rivers. Particular design approaches, water hammer control strategies and critical flow regimes that may induce unacceptable water hammer loads are outlined and discussed. Hydroelectric power plants with relatively short inlet and outlet conduits are analysed with enough accuracy using the rigid column water hammer theory. For systems with long penstocks the elastic column water hammer theory should be used.

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