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HYDRAULIC TRANSIENT CONTROL OF NEW AND REFURBISHED KAPLAN TURBINE HYDROPOWER SCHEMES IN SLOVENIA

BLAŽENJE PREHODNIH POJAVOV V SLOVENSKIH NOVIH IN OBNOVLJENIH HIDROELEKTRARNAH S KAPLANOVIMI TURBINAMI

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Abstract

As a natural resource, water is abundant in Slovenia, and its exploitation for electricity generation has a long history. The construction of Kaplan-type turbines is preferred due to topographical and environmental conditions. Water hammer control strategies, including issues of axial hydraulic thrust calculations, are presented in this paper. The case studies include new and refurbished hydropower plants located on all three major river basins in Slovenia.

Povzetek

Slovenija ima dolgo zgodovino izrabe vodnih virov za proizvodnjo električne energije. Zaradi topografskih in ekoloških omejitev je gradnja hidroenergetskih objektov z visokimi pregradami omejena. V Sloveniji prevladujejo pretočne hidroelektrarne z vgrajenimi kaplanovimi turbinami.

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V tem prispevku so predstavljene strategije nadzora negativnih posledic prehodnih pojavov, vključno s problemi pri izračunih aksialnih hidravličnih sil. Praktični pristop je predstavljen na novih in prenovljenih hidroelektrarnah, ki se nahajajo na povodjih rek Save, Drave in Soče.

1 INTRODUCTION

Together with forests, water is the only true natural resource in abundant supply in Slovenia. With an annual quantity of 17,000 m³ 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 major river basins (catchment areas): Drava, Sava, and Soča. They are characterized by a combination of nival and nival-pluvial regimes. The gross hydropower potential is estimated at 19,440 GWh/year. Thus far, 45% of the total technically available potential has been exploited: 4,115 GWh/year. Hydropower plants generate approximately 30% of the total installed capacity.

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

Electricity generation in Slovenia using hydropower started at the end of the 19th century with the first turbine installed in Škofja Loka, *[2]*. Construction of the Završnica hydropower plant in 1914 and the Fala hydropower plant in 1918 marked a turning point in terms of the electrification of the country.

Major developments were made after 1945 with the return of to Primorska region to Slovenia with its hydropower plants on the Soča River and the systematization of electricity distribution. In the 1960s, the construction of hydropower plants on the Sava and Drava Rivers began, to meet basic demands for electricity and continued through the 1970s. The post-independence period saw interconnection of the Slovenian power grid to the common European network. Construction of the chain of hydropower plants on the lower Sava River began, as did the start of refurbishment of existing facilities.

Regarding the river basins, the Sava River basin is the largest and represents more than 50% of the total country area but is the least utilized in terms of hydropower, with a total installed capacity of 230 MW. Completion of the chain on the lower Sava River is underway, and the start of the procedure for the design of the middle Sava River chain with 10 hydropower plants is foreseen. Unfortunately, political, economic, and environmental issues are hindering the project.

The Drava River basin is the most important and the most developed, with an installed capacity of 600 MW. A comprehensive refurbishment programme has been completed with the replacement of all obsolete electromechanical equipment. The Drava is a border river, and the operating regime of the chain must be co-ordinated with the 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 major hydropower plants have a total capacity of 142 MW and a pump-storage plant at Avče (the only one in Slovenia) completes the Soča River basin utilization with additional 180 MW capacity.

There is also the Mura River, but it is not currently 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 in late spring. This is favourable in comparison 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 natural habitats, *[1].*

2 HYDRAULIC TRANSIENTS

General issues related to hydraulic transients have already been presented, *[3, 4]*. These issues include transient operating regimes, transient control, and modern approaches to transient modelling.

Specific transient issues relating to Kaplan turbines the 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 turbine head cover,
- calculation and measurement of axial hydraulic thrust,
- installation of a surge tank for a low-head Kaplan 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, in which 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.

The transient behaviour of a hydraulic machine can be modelled using the steady-state characteristics (hill chart). Turbine characteristics are given in forms of unit speed, unit discharge and unit torque (n_{11}, Q_{11}, M_{11}) for different guide vane openings A_0 and for different runner blade angles (blade pitch angle) β are used.

Due to the traditionally 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 the basis for the MISI TRANK software package, *[6].* The rigid water hammer 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 in the event of an excessive speed rise, *[8].*

Attention should be paid to reverse water hammer, which 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 the closing of the turbine (guide vanes and runner blades). Two approaches are used in the estimation of the potential danger of full column separation, *[9].*

Turbine head cover pressure criterion. Based on 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 vapour pressure $p_a > p_{vp}$.

Axial hydraulic thrust criterion. The potential danger of full column separation and 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 acting hydraulic thrust 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:

$$\left|F^{-}{}_{a,\max}\right| = \min\left\{\left|F^{-}{}_{ad}\right|, W_u\right\} \tag{2. 1}$$

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:

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

(2)

The dynamic head is calculated with the following equation:

$$\Delta H_i = \frac{Q_{sc} G_d}{g t_{sc}} \tag{2. 2}$$

The installation of air valves has limited influence on the application of the above criterion and cannot prevent damaging reverse water hammer.

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. Over 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 with a 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 (Dravske Elektrarne Maribor). Constructed in 1966, the two units made use of 33-m head at a threshold capacity of 136 MW (160 MW after refurbishment in 2011). The plant is connected to a 17.2-km long trapezoidal profile inlet channel, see Figure 1. The outlet channel is 6.2 km long and joins the Drava River at Ptuj Lake, the largest artificial lake in Slovenia and the headwater level of the Formin HPP, the last hydropower plant on the Drava river.

Each of the two units is equipped with a pressure-regulating valve (PRV) comprised of five vertical vanes connected via a 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. The dimensions of the inlet conduit, scroll casing, and the draft tube are expressed as geometric characteristics. The polar moment of generator inertia is $I = 3.375 \times 10^6$ kgm^2.

***Figure 1**: Zlatoličje HPP (photo www.dem.si.)*

Emergency shut-down of the Kaplan turbine from 75 MW output or 94% of full-load is considered to be one of the most severe normal operating regimes with respect to large transient pressure heads, turbine rotational speed and surges in open channel.

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. The PRV linear full-stroke closing time is $t_{c,\ PRV}$ = 1200 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 headwater level variations (Z_{HWL}) during the period of the turbine closure. 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. Analysis of free surface waves in the inlet and outlet channel is beyond the scope of this paper.

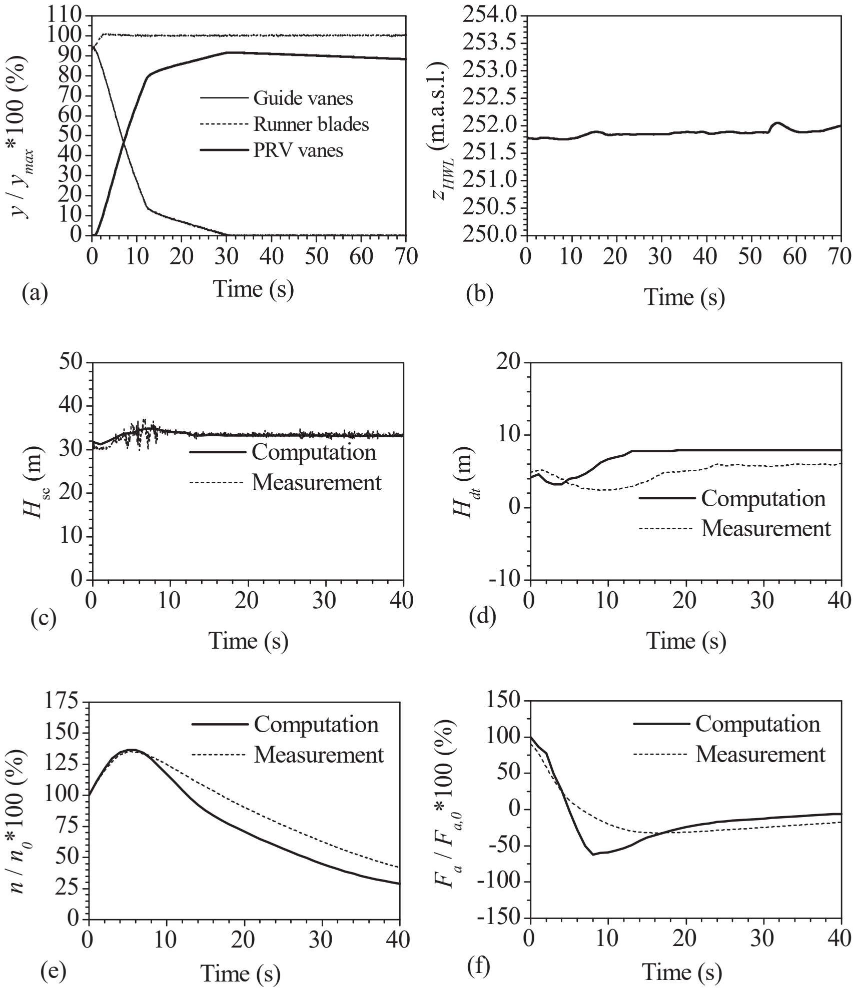


***Figure 2**: Emergency shut-down in Zlatoličje HPP (P = 75 MW): Guide vane and runner blade servomotor strokes (a), headwater level at the turbine inlet (b), scroll case (c) draft tube heads(d), unit rotational speed (e) and axial hydraulic thrust (f)*

The assumed flow-passage system used for rigid water hammer analysis is comprised of relatively short inlet scroll case and outlet (draft tube) conduits. Figure 2(c-f) shows 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 rise of 35% and 36.5%, respectively, (Figure 2(e); n_0 = 125 min^{-1}) 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 model measurements. It is difficult to measure hydraulic quantities in the model at smaller wicket gate openings (large uncertainties), in particular at an increased rotational speed of the turbine. There is also a large uncertainty in the measured axial hydraulic force on the prototype. However, the general trace of calculated and measured axial hydraulic thrust is similar.

4 CASE STUDY 2: KRŠKO HYDROPOWER PLANT

Construction on the lower Sava river reach is currently one of the largest infrastructure projects in Slovenia. Krško HPP is the fourth in a chain of six planned run-of-the-river hydropower plants. Upstream projects include Vrhovo HPP (1993), Boštanj HPP (2006), and Arto-Blanca HPP (2010). On the downstream side, Brežice HPP has been recently put into operation, and Mokrice HPP is under design review. Three Kaplan units with a total installed capacity of 39 MW are in a powerhouse constructed on the right side of the river bank (looking downstream), see Figure 3. Limited construction space, inaccessibility, the vicinity of the main road and the railway with deep excavations due to locally heavily fractured dolomite rock hindered construction in comparison to the other stages on the chain, *[10].*

***Figure 3**: Krško HPP (photo Litostroj Power archive)*

In an effort to lower construction and maintenance costs, the mechanical and civil engineering designs are as uniform as possible. After completion, all hydropower plants in the chain will operate fully automated and unmanned. The polar moment of generator inertia is $I = 700 \times 10^6$

Emergency shut-down of the unit 11.7 MW output is observed. Figure 4 shows results of rigid column water hammer analysis for the considered emergency shutdown.

The agreement between the computed and measured maximum rotational speed rise of 23% and 26.7%, respectively, (Figure 4(b); n_0 = 100 min^{-1}) is good. The same can be said for the maximum scroll case pressure; the calculated value is 14.1 m, and the measured is 14.2 m (Figure 4(c)). 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 1354 kN and 641 kN, respectively, are less than the permissible thrust | $F^{-}_{a,max}$ | = 1943 kN (Figure 4(d)). The general trace of calculated and measured axial hydraulic thrusts is similar.

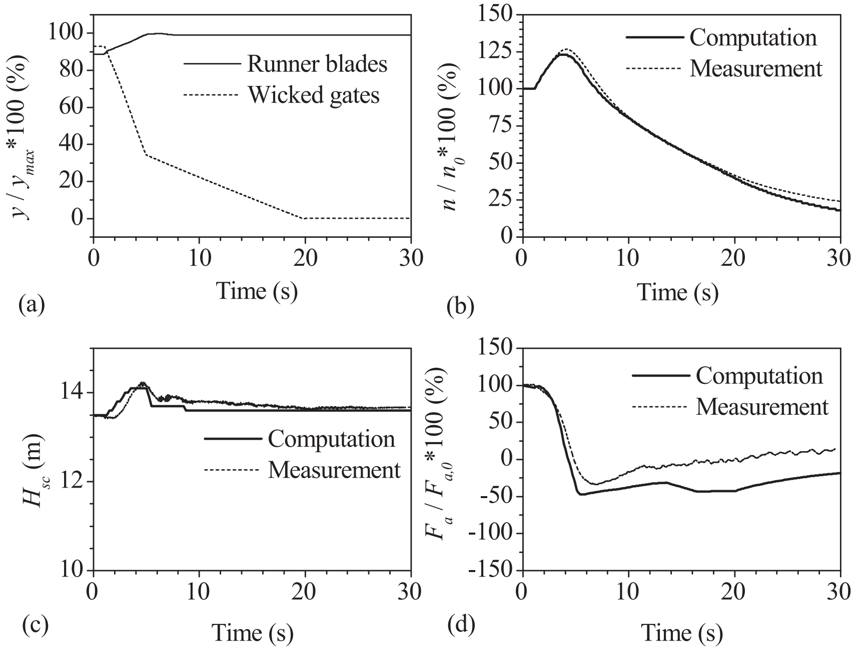


***Figure 4**: Emergency shut-down in Krško HPP (P = 11.7 MW): Guide vane and runner blade servomotor strokes (a), unit rotational speed (b), scroll case pressure (c) and axial hydraulic thrust (d).*

5 CASE STUDY 3: PLAVE II HYDROPOWER PLANT

The design of Plave II HPP on the Soča River basin was based on exploiting the available hydro potential and infrastructure of the existing Plave I HPP, built prior to WWII. Intakes for both HPPs are located at the Ajba dam. 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. The complete length of the tunnel is 6 km with a diameter of 6.4 m and runs parallel to the Plave I HPP channel. The 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 in two sections divided by a gate chamber. A vertical Kaplan turbine of 20.5 MW capacity, is installed in the powerhouse; see Figure 5.

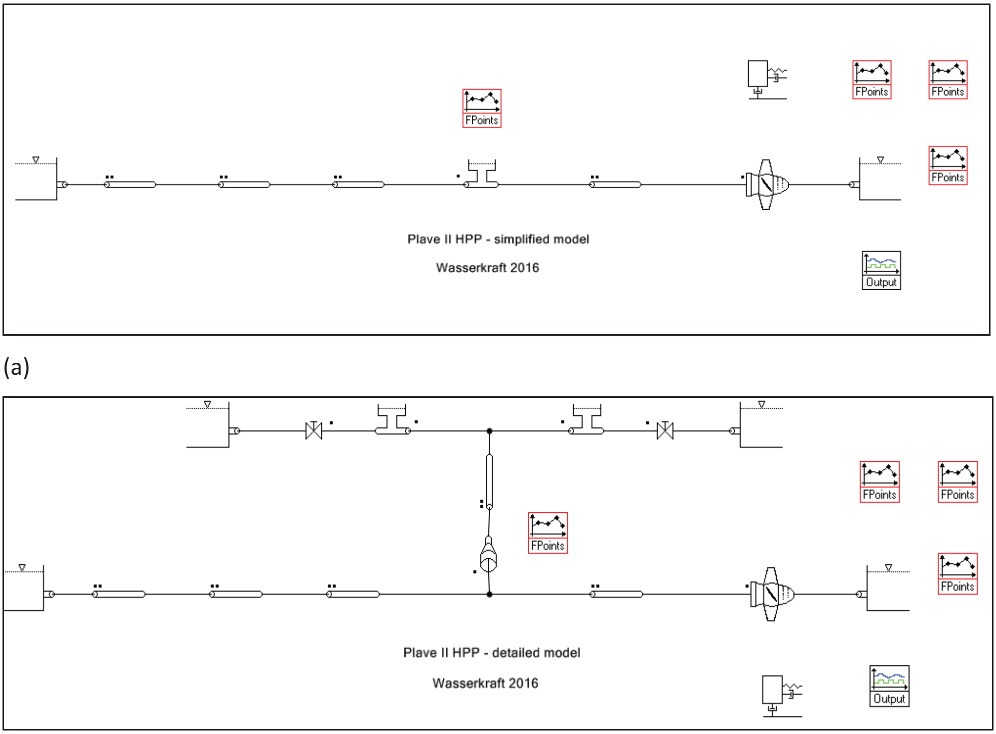
Operation of both Plave I and Plave II HPP is fully unmanned and remotely operated from the control centre.

Due to the long tunnel with a surge tank and relatively long penstock, an elastic column water hammer model has been used, *[5].* A simplified and detailed model of the surge tank will be presented, and results compared to measured values. Attention will be given to penstock pressure, rotational speed and surge tank water levels during emergency shut-down. Figure 6(a) presents the basic or simplified model of the flow-passage. Two surge tanks are replaced in the model with a single equivalent surge tank of 37 m diameter. The value of the surge tank intake losses is k_{in} = 0.00125 s^2/m^5 and outtake losses k_{out} = 0.00078 s^2/m^5. The design of the surge tank and orifice was tested in a hydraulic research laboratory.

Figure 6(b) presents a more detailed model of the flow-passage system. Two surge tanks are included as well as the connecting pipe from the low-pressure tunnel.

***Figure 5**: Plave II HPP machine hall during construction (photo Litostroj Power archive)*

As seen from the results presented in Figure 7, the main difference between the 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 in the connecting pipe between the low-pressure tunnel to the penstock. A minor difference is present for the rotational speed (219 min^{-1} vs. 225 min^{-1}), while there is no difference in the maximum surge tank water level (109.6 m.a.s.l.). A comparison of the measured values confirms the detailed model.



(a)

(b)

***Figure 6**: Plave II HPP computational model*

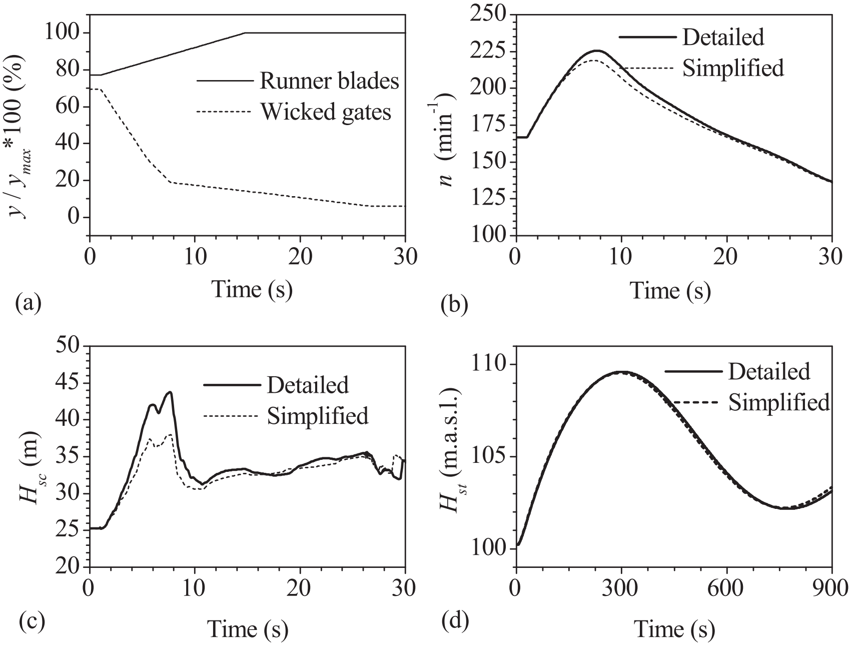


Figure 7*: Emergency shutdown in Plave II HPP: Guide vane and runner blade servomotor strokes (a), unit rotational speed (b), penstock pressure (c) and surge tank water level (d).*

Complete tabulated measured results are not available (different measuring chains in the surge tank chamber and in the machine hall); therefore, a direct comparison is not presented. Figure 8(a) shows measured results for penstock pressure (p_{sp}) and rotational speed (n). Wicket gates and runner blades servomotor strokes are labelled y_2 and y_3, respectively. Figure 8(b) shows results for the surge tank water level oscillations over a prolonged interval during commissioning testing. The emergency shut-down that is taken into consideration is labelled M55.

Note: Figures 8(a) and 8(b) are taken directly from the original commissioning report, [10]; therefore, the text is in its original (Slovenian) language.

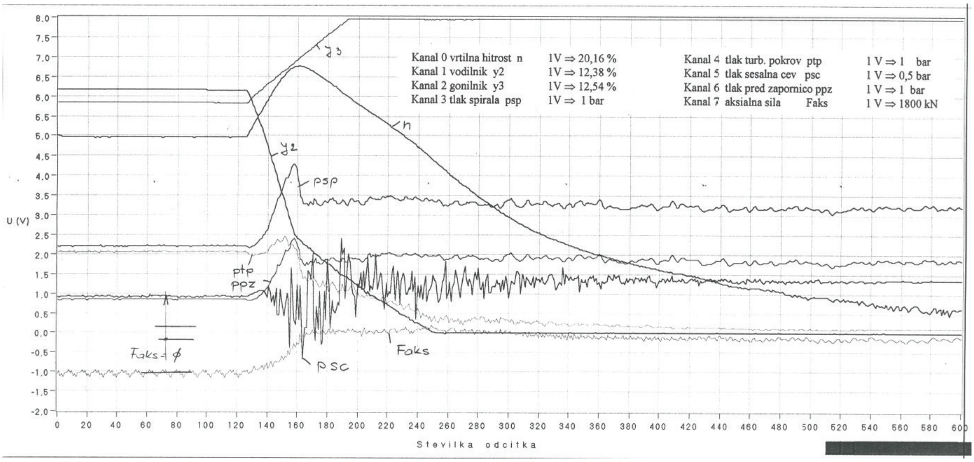


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Figure 8a: Emergency shutdown in Plave II HPP (P = 18 MW): Measured results for guide vane and runner blade servomotor strokes, penstock pressure, and rotational speed

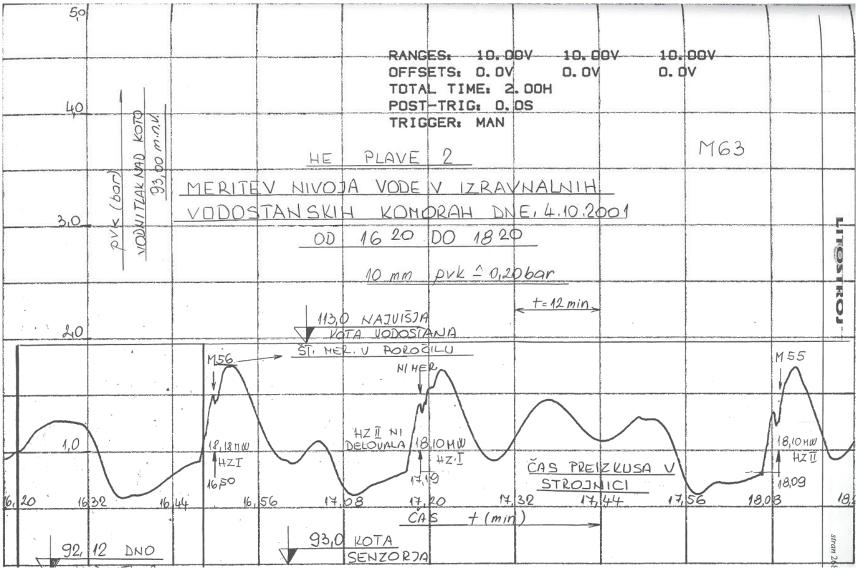

Figure 8b: Emergency shutdown in Plave II HPP (P = 18 MW): Measured results for surge tank water level oscillations

6 CONCLUSIONS

This paper presents three typical case studies of water hammer control strategies of Kaplan turbine hydropower plants in Slovenia. Particular design approaches, water hammer control strategies, and critical flow regimes that may induce unacceptable water hammer loads are outlined. Hydroelectric power plants with Kaplan turbines are traditionally comprised of relatively short inlet and outlet conduits; therefore, the rigid column water hammer theory is used for these cases. For systems with long penstocks, elastic column water hammer theory should be used.

Acknowledgments

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Nomenclature

(Symbols)	(Symbol meaning)
D	runner diameter
d	turbine shaft diameter
F_a	axial hydraulic thrust
F^-_{ad}	damaging axial hydraulic thrust acting upwards
$F^-_{ad,max}$	maximum axial hydraulic thrust acting upwards
G_d	geometric characteristics of the draft tube
G_u	geometric characteristics of the inlet conduit and the scroll-casing
g	gravitational acceleration
H	pressure head
H_s	suction head
H_{dt}	draft tube head
H_{sc}	scroll case pressure
ΔH_i	dynamic head
I	polar moment of inertia
K	surge tank head losses (intake, outake)
n	turbine rotational speed
P	turbine output
p	pressure
Q	discharge
Q_{sc}	discharge at an assumed water column separation
t_{sc}	closing time from discharge Q_{sc} to $Q = 0$ m^3/s
y	servomotor (guide vanes/runner blades) stroke
W_u	weight of the unit rotating parts
Z_{hwl}	headwater level
Z_{twl}	tailwater level
ρ	mass density