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HYDRAULIC TRANSIENT CONTROL OF REFURBISHED FRANCIS TURBINE HYDROPOWER SCHEMES IN SLOVENIA

BLAŽENJE PREHODNIH POJAVOV V SLOVENSKIH HIDROELEKTRARNAH Z OBNOVLJENIMI FRANCISOVIMI TURBINAMI

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Keywords: hydraulic transient regimes, Francis turbine, transient control strategies, computational model, field tests

Abstract

This paper presents hydraulic transient control methods of refurbished Francis turbine hydropower schemes in Slovenia. Transient control strategies are presented, including the alteration of operational manoeuvres, transient control devices, suitable water conveyance system layout and operational limits. Computational models and modern hydraulic transient control approaches are also outlined. The paper concludes with the practical implementation of two case studies: the refurbishment of Moste HPP and Doblar 1 HPP. Both hydropower plants are equipped with Francis turbine units and underwent refurbishment in 2010 to 2013, respectively.

Povzetek

Prispevek obravnava metode za blaženje negativnih posledic hidravličnih prehodnih pojavov v slovenskih hidroelektrarnah z obnovljenimi francisovimi turbinami. Negativne posledice prehodnih pojavov pojavov lahko blažimo s spremembo obratovalnih manevrov, vgradnjo varnostnih elemen-

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tov in ustreznim načrtovanjem pretočnega sistema hidroelektrarne. Predstavljen je moderni pristop k modeliranju in izbiri ustreznih metod. Praktični pristop je prikazan na dveh industrijskih primerih, HE Doblar 1 in HE Moste, ki imata kot pogonske agregate vgrajene francisove turbine in sta bili obnovljeni v letih 2010 do 2013.

1 INTRODUCTION

The refurbishment and upgrading of hydropower plants (HPP) are a growing concern in the hydro industry. The safety, efficiency, availability, and profitability of the plant should be investigated when considering the refurbishment and upgrading of it. The work may include the overhaul and/or replacement of components which are most affected by wear or the installation of new machinery. The increase of the output is normally achieved by improvement of the turbine efficiency and by increasing the turbine discharge. The increase of discharge and flexibility of load variation may result in much higher dynamic loads on both refurbished and non-refurbished plant components. The feasibility and design studies of a refurbished hydropower plant should include hydraulic transient analysis in order to ensure the safe and economic operation of the plant. Hydraulic transients are flow disturbances caused by a change from one steady state to another, [1]. Disturbances result in pressure changes induced by the propagation of pressure waves through the water conveyance system. The magnitude of the pressure changes associated with hydraulic transients can be large enough to cause serious damage to the system components, devices, and pipeline segments (e.g. pipe rupture). In addition, hydraulic transients can jeopardize the economic viability of the design, forcing the hydropower plant owner to spend a considerable amount of money in the form of prolonged and expensive repairs for leaks, breaks, poor system performance and increasing frequency of component damage, failure, and emergency maintenance, [2]. Awareness of the risks of hydraulic transients has led to significant progress in recent decades, especially after the introduction of the personal computer and special commercial software packages with continuing development and expansion into other technical fields, in which other types of transients (wind, electrical, open channel flow) are present. This has resulted in the consideration and inclusions of a transient analysis for most hydropower and other design projects. However, there is a strong need for further work on the development of a special guideline on hydraulic transients in hydropower plants that would bring together pieces from existing standards and guidelines, [3].

The first part of the paper is focused on transient operating regimes, hydraulic transient control strategies and a computational model used for numerical analysis. Particular attention is given to the role of the responsible engineer and modern hydraulic transient approaches. The second part of the paper presents a practical implementation of hydraulic transient analysis. Using commercial computer software, comparisons between computational and field measurements results are presented. Litostroj Power has more than 50 years of experience in the field of hydraulic transients for turbine and pump systems.

2 HYDRAULIC TRANSIENT OPERATING REGIMES

The main source of hydropower plant transients are operational manoeuvres of the turbine. During steady-state conditions, the load of the turbine equals the load of the generator. Any change of the current operational condition will result in the response of the turbine governor and, consequently, in the variation of the turbine rotational speed and pressure in the water conveyance system.

Transient loads are induced by a number of operating regimes. These may be classified as follows, [1], [3], [4]:

(1) *Normal transient operating regimes*
All hydraulic transient control devices in the system are assumed to be functioning as designed. These regimes include turbine start-up and load acceptance, load rejection under governor control and emergency shut-down.
(2) *Emergency operating regimes*
In this case, one of the control devices is malfunctioning leading to partial turbine runaway, closure of the turbine inlet valve (butterfly, spherical).
(3) *Catastrophic (exceptional) operating regimes*
Several control devices are malfunctioning in the most unfavourable manner; these may include full turbine runaway and closure of the surge tank butterfly valve under full discharge.

Additional operating regimes for transient analysis can be selected either by the hydropower plant owner or by the engineer responsible for the analysis:
(1) full load acceptance of the unit followed by full load rejection of the unit in the critical time interval to produce the maximum water level in the surge tank,
(2) full load rejection of the unit followed by full load acceptance of the unit in the critical time interval to produce the minimum water level in the surge tank,
(3) full load rejection with the wicket gates cushioning stroke inoperative,
(4) closure of the turbine inlet valve at set over-speed after full load rejection,
(5) rapid closure of the wicked gates (reaction turbine) or nozzle (action turbine) in less than the wave reflection time $T = 2L/a$ (L = conduit length; a = wave speed).

In pump-turbine plants, hydraulic transients in pumping mode of operation should also be investigated. Apart from this, the pump-turbine (turbine) unit might operate in synchronous compensation mode. Water column separation (transient cavitation) and resonance should be avoided in hydropower schemes whenever possible.

3 HYDRAULIC TRANSIENT CONTROL

Hydraulic transient loads can be kept within the prescribed limits (e.g., pressure in the flow-passage system, turbine rotational speed, surge tank water level, etc.) with the methods that fulfil the following criteria [5]:
(1) ensure the safety of the plant and personnel during any hydraulic transient regimes,
(2) identify the most severe adverse conditions and take adequate measures to ensure that hydraulic transient parameters remain within the design values,
(3) establish reasonable design limits for specific operational parameters.

The installation of a transient control device itself does not guarantee safety and can introduce additional risk into the system. If the control device is not fault-tolerant, redundancy is required, accompanied by increased inspections and maintenance costs, [2]. Operational, safety, and economic factors are therefore decisive for the selection of protection against undesirable hydraulic transient effects. The best solution may be a combination of different design approaches, [3], [4].

(1) Alteration of operational regimes. This includes appropriate control of the wicket gate manoeuvres and shutoff valve closing/opening times. A two-speed wicket gate closing time function with an added cushioning stroke is recommended. Alteration of the operating regime is the most efficient method for hydraulic transient control in cases of refurbished hydropower plants due to the low cost of the work involved.

(2) Installation of surge control devices in the system. The protective devices are installed on the water conveyance system as system components in order to alter the overall system characteristics (shorten the active conduit length, reduce the effects of liquid compressibility, increase the turbine inertia).

The protective devices may include:
(i) increased turbine unit inertia (adding flywheels to small units, increasing the generator inertia),
(ii) resistors (to absorb excessive power),
(iii) surge tank in headrace and/or tailrace (shortens the active conduit length, improves governing stability) or air cushion surge chamber (more complicated, requires compressed air supply),
(iv) pressure-regulating valve (operates synchronously with the turbine guide vane mechanism),
(v) pressure-relief valve (opens at a set pressure, small units),
(vi) rupture disc (bursts at a set pressure, small units),
(vii) aeration pipe (attenuates water column separation effects) or air valve (attenuates water column separation effects, reduces negative axial hydraulic thrust); both release unwanted air from the pipeline.

(3) Redesign of the water conveyance system layout. Redesign together with corresponding operational regimes is the most efficient method for hydraulic transient control in the case of new hydropower plant developments while there are severe cost constraints for the redesign of the water conveyance system layout in case of refurbished hydropower plants (civil works). It should be noted that the rehabilitation process offers the advantage of allowing comparative hydraulic transient tests in the plant before and after rehabilitation. In contrast, the design of a new plant is based on industry guidelines and good engineering practice.

4 HYDRAULIC TRANSIENT ANALYSIS

Hydraulic transient analysis is traditionally undertaken with deterministic models, [1], that treat a number of transient regimes based on experience, guidelines, and codes. In addition, parametric analysis accounts for uncertain parameters (e.g., skin friction, wave speed, entrained air). The tasks and responsibilities of the hydraulic engineer are to identify and treat transient regimes that may cause operational problems or endanger the safe operation of the hydropower plant and its personnel and to provide solutions for a safer and more economical operation. From the aforementioned scope of possibilities regarding hydraulic transient operation and prevention (Sections 2 and 3), it is clear that the engineer must have a broad interdisciplinary range of knowledge in different fields of engineering. The extent of analysis will depend on the particular owner specifications, type of machine, the complexity of the water conveyance system and design phase. The plant owner can specify transient regimes for analysis according to a planned sequence of operation of the hydropower plant. The type of machine will govern the use characteristics and also influence the complexity of the water conveyance system. Hydraulic transient analysis can be, at an early stage of the design process (preliminary, conceptual design), performed with simplified models that treat hydraulic transient regimes based on experience, guidelines, and codes, [1], [3], [6]. In the early stage of design, appropriate methods for limiting transient loads can be selected, especially the change of the conduit profile, the dimensions and the positions of the system components. In the later stage of the design process, numerical methods, [1], [7], are applied, the detailed transient regimes are identified, and the surge control devices are selected. The analysis should include cases with extreme values of discharge and heads when either one unit or all units operate, cases with malfunctions of one of the devices and cases with unfavourable sets of events. These results form the basis for risk analysis to transients in hydropower plants, [8]. During the commissioning of the hydropower plant, the engineer should assist the commissioning team in the field with additional analysis in cases in which the on-site boundary conditions differentiate from those assumed in the detailed design.

There are a number of commercial software packages available and adequately verified by vendors and end users. The same applies to in-house software codes. The hydraulic transient analysis in this paper is performed using the SIMSEN commercial computer software package, [9]. This software is based on a modular structure and composed of objects, each representing a specific element in the network. Each element includes a set of differential equations based on the network element model. Hydraulic elements are modelled as RLC electrical circuits according to the impedance method, [10], in which the unknown quantities are (1) piezometric head h at the node and (2) the discharge Q through each component, corresponding to the voltage U and current i, respectively. The following mass conservation and momentum equations provide the basis for an equivalent electrical circuit modelling; see Figure 1, [11],

$$\frac{\partial h}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0, \tag{4.1}$$

$$\frac{\partial h}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{fQ|Q|}{2gDA^2}=0. \tag{4.2}$$

Note that all symbols are defined in the Nomenclature. A quasi-steady approach for estimating skin friction losses in the pipeline is adopted for slow transients. Equations (4.1) and (4.2) are solved by using the finite difference method [11]. This approach leads to a system of ordinary differential equations that can be represented as a T-shaped equivalent scheme as depicted in Figure 1. The RLC parameters of this equivalent scheme defined for a length dx are, [11],

$$R=\frac{f|Q|}{2gDA^2}dx, \quad L=\frac{1}{gA}dx, \quad C=\frac{gA}{a^2}dx. \qquad (4.2)$$

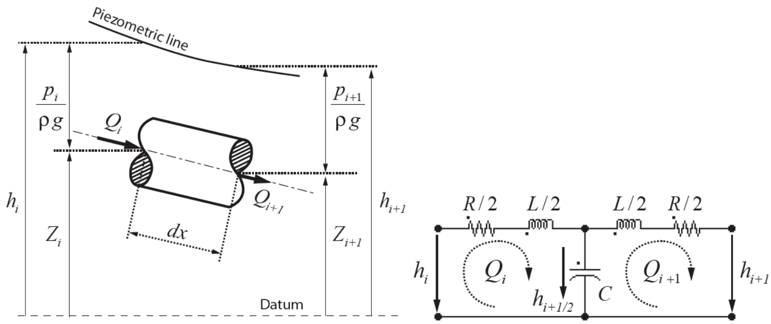

Figure 1: Modelling of a pipe of length *dx* (left) and a corresponding equivalent scheme, [10]

Boundary conditions (valve, surge tank, Francis turbine, etc.) are also defined as RLC elements. For example, the Francis turbine boundary condition represented as a set of RLC elements is depicted in Figure 2. Assuming that the transition between two operating points of a turbine corresponds to a succession of steady-state points, the transient behaviour of a hydraulic machine can be modelled using the steady-state characteristics (hill chart). Turbine characteristics given in the form of unit speed (n_{11}), unit discharge (Q_{11}) and unit torque (M_{11}) are used in SIMSEN. RLC models of pipes and of boundary conditions are set-up using Kirchoff's laws. The time domain integration of the full hydropower system is carried out with a Runge-Kutta fourth-order procedure, [11].

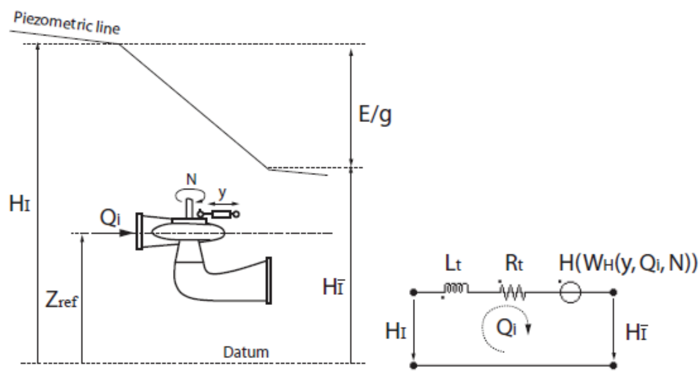

Figure 2: Francis turbine model (left) and a corresponding equivalent scheme [10]

5 TRANSIENTS IN THE DOBLAR 1 HYDROPOWER PLANT

The Doblar 1 HPP is a storage/run-of-river hydropower plant on the Soča river in Slovenia and has been in continuous operation since 1939. The original turbine equipment (3 units) was manufactured by Riva Milano and until 1947 produced electrical energy for the Italian grid with a grid frequency of 42 Hz. In 1950, the plant changed ownership and, together with the rest of the Slovenian grid, changed to a grid frequency of 50 Hz. Unit 1 was refurbished in 2001 with a turbine manufactured by Litostroj, and all three units were refurbished and upgraded from 2010 to 2013.

The water conveyance system is a complex combination of the following elements: headrace tunnel with a length of 3735 m and 5.6 m diameter, surge tank system including two ellipse-shaped orifice surge tanks (combined cross section area 880 m² with 12 orifices) and cylindrical surge shaft, three parallel penstocks with a length of 46 m and 3.0 m diameter, three 9.5 MW vertical shaft Francis turbine units of rated head H_r = 46.0 m and rated discharge Q_r = 25.0 m³/s each connected to its own downstream surge tank and tailrace tunnel, and downstream reservoir; see Figures 3 and 4. The rated speed of the turbine is n_r = 300 min^{-1} and the polar inertia of the unit rotating parts is I = 84.70×10³ kgm². Each turbine is equipped with a spherical turbine inlet valve with a diameter of D_v = 2.3 m. Due to the age of the hydropower plant and the historical context of the hydropower plant location (change of the country ownership after the Second World War) limited drawings of the upstream and downstream surge tank system were available. Careful on-site surveying established a more detailed picture for the hydraulic transient modelling calibration.

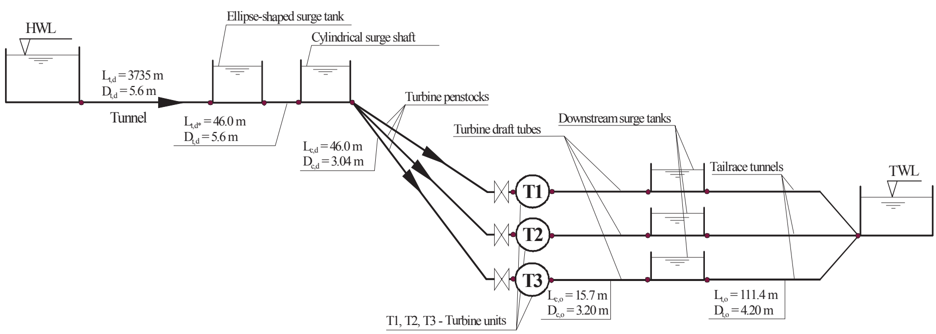

Figure 3: *Layout of Doblar 1 HPP, Slovenia*

The results for the simultaneous sudden full-load rejection of the three turbine units [12], [13], are presented, including guide wicket gates position (y), turbine rotational speed (n), and turbine inlet (H_{ti}) and draft tube pressure heads (H_{dt}); see Figure 5. The units are operating at generator output $P_{gen,1}$ = 11.0 MW, $P_{gen,2}$ = 11.0 MW, $P_{gen,1}$ = 11.0 MW and headwater level HWL = 152.4 m.a.s.l. The turbines are disconnected from the electrical grid after a period of steady-state operation. The electromagnetic torque of the generator drops to zero instantaneously; as a result, the turbine rotational speed of each unit increases. The closure of the wicket gates with the prescribed two-speed closing law to speed no-load reduces the hydraulic torque and consequently limits the maximum turbine rotational speed and pressure oscillations in the flow passage system.

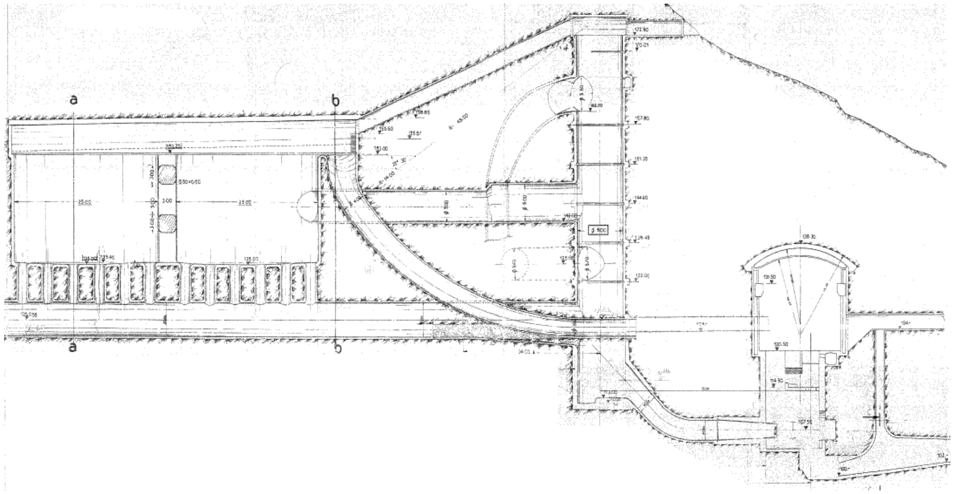

Figure 4: *Layout of the upstream end surge tank system in Doblar 1 HPP, Slovenia*

Results are validated for Unit 3. As seen from Figure 5, the maximum calculated turbine inlet pressure head $H_{ti,max,c}$ = 44.2 m is higher than the measured one $H_{ti,max,m}$ = 43.0 m. A good comparison can be observed during the wicket gate closing sequence, while the measured values of the turbine inlet pressure oscillate at a higher level due to the cylindrical surge shaft influence (inflow from the ellipse-shaped surge tanks). The maximum calculated turbine speed $n_{max,c}$ = 405.5 min^{-1} is higher than the measured one $n_{max,m}$ = 391.5 min^{-1} and the calculated maximum draft tube pressure head $H_{dt,max,c}$ = 3.9 m is also higher than the measured head $H_{dt,max,m}$ = 1.8 m (average of peak values). During the wicket gates closing sequence and speed no-load operation, high-frequency pulsations are present at draft tube pressure measurements (noise).

Figure 6 shows a comparison between the calculated and the measured water level oscillations in the cylindrical surge shaft (Z_{ss}) and the turbine inlet pressure for a longer time interval. During the wicket gate closing sequence, the ellipse-shaped surge tanks have no influence on the turbine inlet pressure but contribute to the cylindrical surge shaft oscillations with an additional discharge through the connecting tunnel between the surge tanks and the surge shaft. The overall discrepancies between the computed and the measured results might be contributed to a simplified modelling of a complex surge tank system and uncertain data on the inlet-outlet losses for both surge tanks.

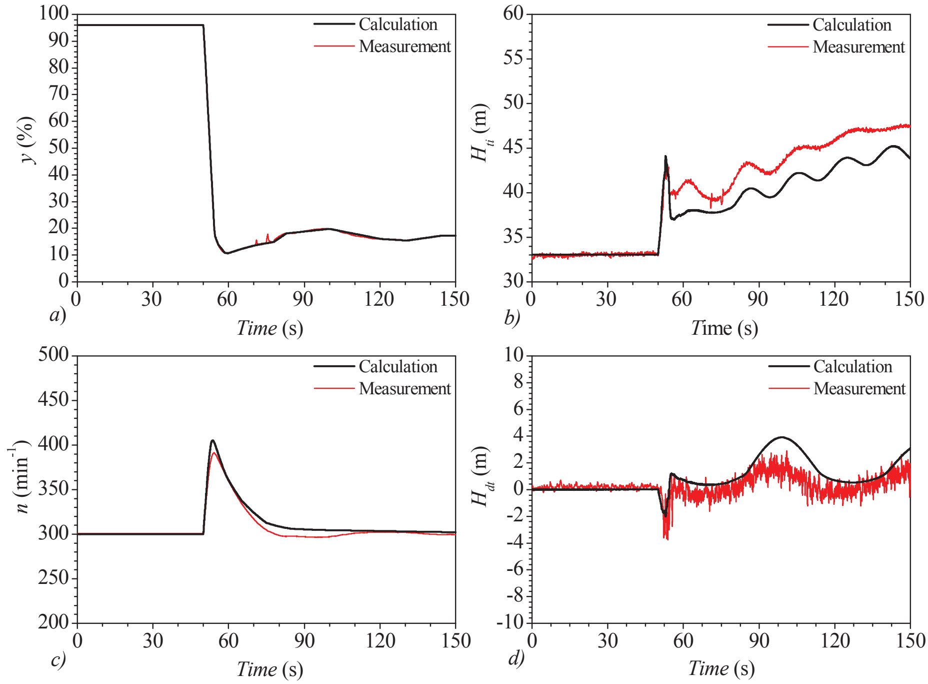

Figure 5: *Comparison of computed and measured results after simultaneous sudden load rejection of the three units; Doblar 1, Slovenia*

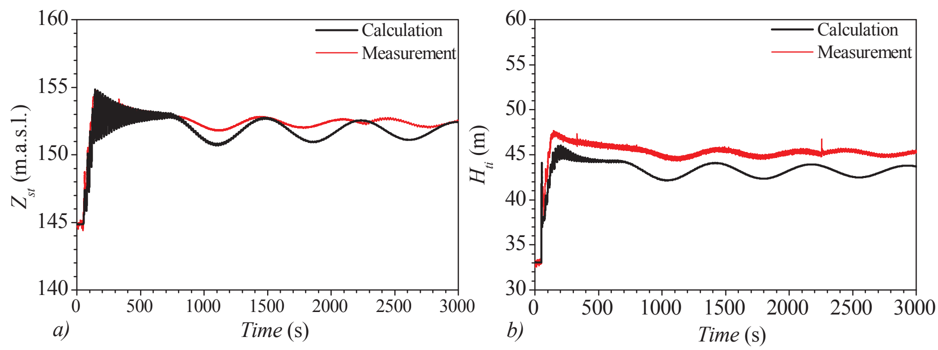

Figure 6*: Water level oscillations in upstream cylindrical surge shaft and pressure for Unit 3 for the case of simultaneous sudden load rejection of the three units; Doblar 1, Slovenia*

6 TRANSIENTS IN THE MOSTE HYDROPOWER PLANT

The Moste HPP was the first hydropower plant on the Sava River, Slovenia, in 1952. The concrete arch-gravity dam lies in the narrowest portion of the Sava Canyon, in the Kavčke gorge below Žirovnica, which with its 60 m height is also the highest dam in Slovenia. The storage reservoir enables a weekly management of the flows. Moste HPP was designed as a storage power plant for the production of peak energy. The original configuration of Moste HPP together with Unit 4, which exploits the hydro potential of the Završnica Creek (Završnica River water conveyance system), represents a complete energy system; see Figure 7. The Završnica HPP was built in 1914 as one of the first large hydropower plants in Slovenia. It was equipped with two horizontal-shaft 1.1 MW Pleton turbines with additional flywheels, both manufactured by Tönnis Ljubljana. In 2005, after 90 years of operation, production stopped, and HPP Završnica became a technical museum. In the first stage, three vertical shaft Francis turbine 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 Francis type pump-turbine unit. The system was designed so as to allow the pumping of the water from the Sava River into the Završnica storage reservoir during surplus energy production which, unfortunately, due to the pollution of the Sava River, ceased to operate. Because of this, 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 units with two larger units. The space of Unit 2 was abandoned and used for the construction of a reinforced powerhouse so as to decrease the unfavourable effects of the powerhouse structure deformation.

Transient events in the Sava River water conveyance system are presented in this paper. The system is comprised of an upstream reservoir, a headrace tunnel with a length of 840 m and a diameter of 3.0 m, a surge tank with lower and upper side galleries, a penstock with a length of 152.5 m and a diameter of 2.6 m, two vertical-shaft 7.5 MW Francis units of rated head H_r = 58.07 m and discharge Q_r = 13.0 m^3/s which are connected to a common tailrace tunnel, measuring 1500 m in length and 4.0 m in diameter, and a downstream reservoir.

The headwater level (*HWL)* is in the range from 510.0 m.a.s.l. to 524.75 m.a.s.l.; the tailwater level (*TWL*) is in the range from 454.28 m.a.s.l. to 457.90 m.a.s.l. The rated speed of the turbine is n_r = 500.0 min^{-1} and the polar inertia of the unit rotating parts is I = 20.25×10³ kgm². Each of the turbines is equipped with a butterfly turbine inlet valve with a diameter D_v = 1.6 m. The turbine inlet valve and the spiral casing centrelines are at the same level of 457.53 m.a.s.l.

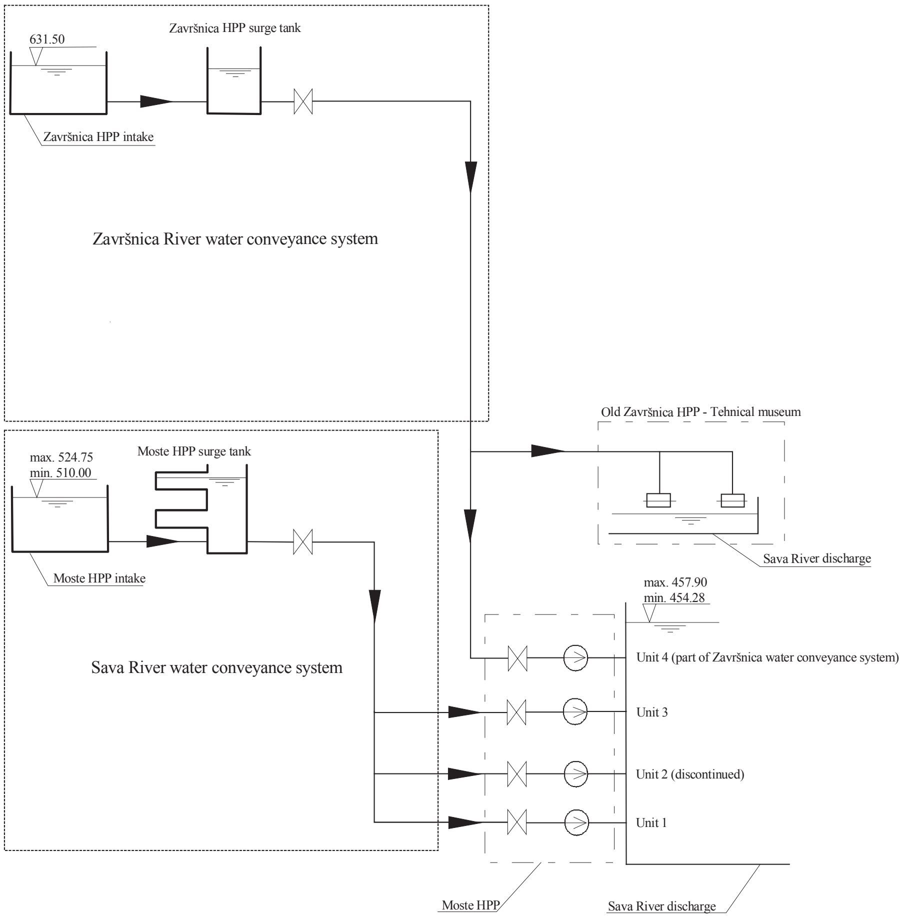

Figure 7: *Sava and Završnica Rivers water conveyance systems*

Various operating regimes were performed during the commissioning tests of new units, including turbine start-up, load acceptance, sudden load rejection, emergency shutdown and closure of one or two turbine inlet valves under various flow conditions. The resulting water hammer was controlled by the appropriate adjustment of wicket gates and turbine inlet valve closing manoeuvres. The computed and the measured results from the sudden simultaneous full-load of two turbines are compared, [13], [14]. The units are operating at a generator output $P_{gen,1} = P_{gen,2}$ = 6.7 MW and headwater level at *HWL*= 524.75 m.a.s.l. The pressure head at the turbine inlet H_{ti}, the turbine rotational speed n and wicket gates position y are shown in Figure 8. The calculated maximum head $H_{ti,max,c}$ = 87.3 m is higher than the measured one $H_{ti,max,m}$ = 81.5 m. As can be seen from the results, the maximum computed turbine inlet pressure head exhibits a peak value during the wicket gate cushioning stroke; there is no such peak at measured results. There is good agreement between the results of computations and measurements in the initial phase of the wicket gate closing event. The calculated maximum turbine rotational speed $n_{max,c}$ = 711.5 min^{-1} is higher than the measured turbine rotational speed $n_{max,m}$ = 696.2 min^{-1}.

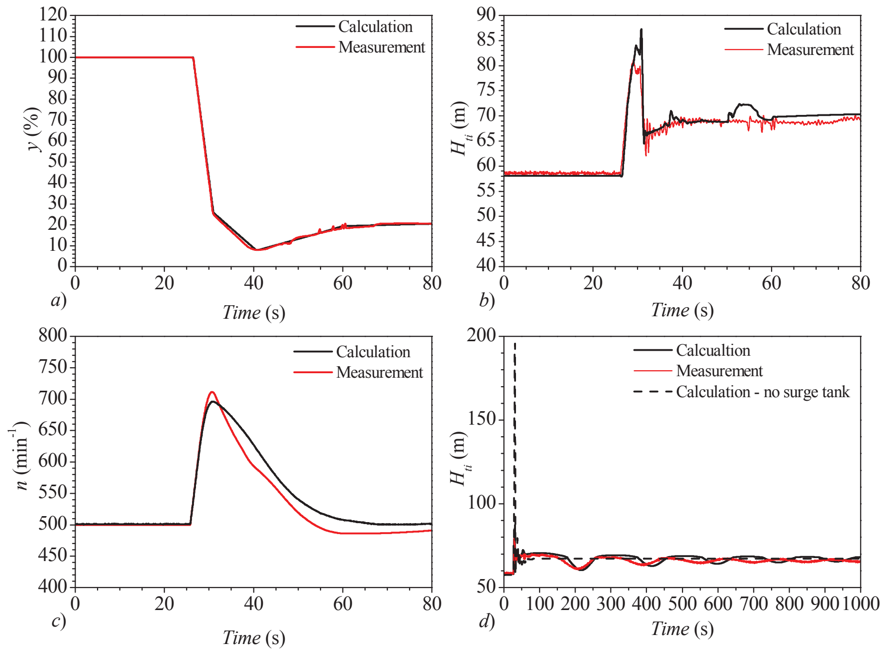

Figure 8: *Comparison of computed and measured results after simultaneous sudden load rejection of the two units; Moste HPP, Slovenia*

Figure 8d shows turbine inlet pressure head oscillations over a longer period. The beneficial effects of the surge tank on water hammer loads during sudden full-load rejection can be observe: the computed maximum head $H_{ti,max,c}$ = 87.3 m of the system with a surge tank is much lower than the computed maximum head $H_{ti,max,c}$ = 194 m of the system without the surge tank.

7 CONCLUSIONS

This paper presents an overview of the hydraulic transient analysis of refurbished Francis turbine hydropower schemes with complex water conveyance systems in Slovenia. The undesirable transient effects may disturb the overall operation of the plant and damage the system components. The introduction of the personal computer and, as a consequence, the development of special commercial software packages has increased awareness towards the importance of hydraulic transient analysis. Nevertheless, the engineer must have a broad interdisciplinary range of technical knowledge. Operating regimes for analysis and subsequent transient control must be selected according to the characteristics of the power plant scheme bearing in mind safety, reliability, and costs. Complete documentation of the water conveyance system is especially important in cases of refurbishment. Two case studies of refurbishment have been presented; the Doblar I hydropower plant on the Soča River and the Moste hydropower plant on the Sava River. In both cases, the hydraulic transient control devices are turbine governors coupled to the wicket gates servomotor with a two-stage stroke and surge tank(s). RLC equivalent scheme modelling computational results agree well with the results of the measurements.

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Nomenclature

(Symbols)	(Symbol meaning)
A	pipe area
a	water hammer wave speed
C	capacitance

dx	distance along the pipe
D	pipe diameter, diameter
f	Darcy-Weisbach friction factor
g	gravitational acceleration
H	pressure head, head
h	piezometric head
I	polar inertia
L	conduit length, inductance (equation 4.2)
M	torque
n	rotational speed
P	output power
p	pressure
Q	discharge
R	resistance
T	wave reflection time
t	time
W_H	Suter head characteristic (Figure 2)
Z	water level
ρ	density
(Subscripts)	(Subscripts meaning)
c	calculated
dt	draft tube
gen	generator
in	inflow
m	measured
max	maximum
out	outflow
r	rated value
ss	surge shaft
ti	turbine inlet
v	valve
0	initial conditions
11	unit value
1,2..	number of the unit
(Superscripts)	(Superscripts meaning)
(Abbreviations)	(Abbreviations meaning)

HWL	Headwater level
RLC	Resistance-inductance-capacitance
TWL	Tailwater level

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