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Water hammer issues in refurbishment of a high-head hydropower plant equipped with Francis turbine

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Abstract. Refurbishment and upgrading of ageing hydropower plants contribute to increase of renewable energy share in modern electrical grid systems. The potential increase of discharge and flexibility of load variation may result in much higher dynamic loads on both refurbished and non-refurbished plant components during transient operating events. First, water hammer control strategies are outlined including operational scenarios, surge control devices, redesign of the pipeline components, or limitation of operating conditions. Water hammer models and solutions are briefly discussed in the light of their capability, availability and uncertainty. The core of the paper is devoted to investigations of water hammer effects in a high-head hydropower plant Piva, Montenegro which is currently in the final phase of refurbishment. The flow-passage system of the Piva HPP is comprised of the intake structure, followed by three parallel penstocks each with Francis type water turbine at the downstream end. The outlet part starts with three parallel draft tubes that are connected to a common lower orifice-type surge tank followed by tailrace tunnel and outlet structure. Computed and measured results for a selected emergency shut-down (ESD) of one turbine form full-load are compared and discussed. Then the validated computational model is used for simulation of ESDs for a wide operating range.

1. Introduction

Refurbishment and upgrading of ageing hydropower plants contribute to increase of renewable energy share in modern electrical grid systems. Key issues in the refurbishment and upgrading include safety, efficiency, availability and profitability of the renovated plant. The refurbishment may include overhaul or replacement of some critical components of the turbine unit and flow-passage system or installation of completely new components. The potential increase of discharge and flexibility of load variation may result in much higher dynamic loads on both refurbished and non-refurbished plant components during transient operating events. The main objective of this paper is to present, discuss and assess the critical parameters which may cause unacceptable water hammer loads in a high-head hydropower plant (HPP) Piva in Montenegro which is in the final stage of refurbishment. The water-conveyance system of the Piva HPP is comprised of the intake structure, followed by three parallel penstocks of different lengths each with a high-head Francis type water turbine at the downstream end. The outlet part starts with three parallel draft tubes that are connected to a common lower (downstream end) orifice-type surge tank followed by tailrace tunnel and outlet structure.

Water hammer is transmission and reflection of pressure waves along the pipeline usually resulting from a rapid change in flow velocity. The magnitude of the pressure fluctuations associated with water hammer can be large enough to cause serious damage to system components. In case of hydropower plants water hammer is normally caused by: (i) unit shutdown or start-up, (ii) load rejection or load acceptance, (iii) emergency shut-down and (iv) electrical faults (earth fault, short-circuit, out of phase synchronization) [1], [2]. In addition, turbine runaway [3] and shutoff valve closure [4] may induce excessive water hammer loads. Changes of discharge induce high pressure fluctuations in the piping system, turbine over-speed, surge tank oscillations and disturb overall operation of the system. The engineers should be able to predict water hammer events, keep the transient loads within the prescribed limits and select critical dimensions of the water conveyance system with appropriate safety margins [5], [6]. Therefore, water hammer control strategies are outlined first including operational scenarios (closing and opening laws), surge control devices, redesign of the pipeline components, or limitation of operating conditions. Water hammer models and solutions are briefly discussed in the light of their capability, availability and uncertainty. In this paper water hammer analysis is performed using a basic version of the commercial computer software package SIMSEN Version 3.3.2 [7]. Then computational and measured results are presented, compared and discussed. A particular attention is paid to emergency shut-down of the turbine unit(s) that is considered to be the most severe normal operating transient regime.

2. Water hammer control

Excessive water hammer loads may disturb overall operation of hydraulic systems and damage the system components. Water hammer in hydro power plants can be kept within the prescribed limits (pressure in the flow-passage system, turbine rotational speed, surge tank water level oscillations) with the following methods [1], [8-11]:

(1) **Alteration of operational regimes** usually includes appropriate control of the wicket gates manoeuvres (turbine governor and servomotor mechanism) and shutoff valve closing/opening times. A multi-speed wicket gate closing time function with an added cushioning stroke is recommended for safer operation of the plant. An important feature is an appropriate closing/opening time sequence for combined operation of the valves and gates.

(2) **Installation of surge control devices in the system.** The protective devices are installed along the inlet and outlet conduit or added to the system components. These control devices alter the system characteristics (shorten the active pipe length, reduce the liquid compressibility, increase the turbine unit inertia) and consequently, the rate of the flow velocity change or/and wave speed is/are reduced. The protective devices may include:

- increased turbine unit inertia (adding flywheel, increasing the generator inertia),
- resistors (to absorb excessive power)
- surge tank in headrace and/or tailrace (shortens the active pipeline length, improves the governing stability),
- air cushioning surge chamber (usually requires compressed air supply),
- one way surge tank (prevents water column separation),
- pressure regulating valve (operates synchronously with the turbine wicket gates),
- safety valve (opens at a set pressure),
- rupture disc (bursts at a set pressure),
- aeration pipe (attenuates effects of water column separation),
- air valve (attenuates effects of water column separation, reduces negative axial hydraulic thrust).

(3) **Redesign of the pipeline layout** e.g. changes of flow-passage profile (high point) and dimensions (diameter, length), different position of system components (valve, surge tank).

(4) **Limitation of operating conditions** include reduced discharge and limited head range. This measure may be considered as temporary one before more effective surge strategy is found.

Operational, safety and economic factors are decisive for selection of the type of protection against the undesirable water hammer effects. A number of alternatives should be investigated before the final design, which may include a combination of various design approaches. In the case of refurbishment and upgrading of hydraulic machinery, the most convenient water hammer control device is the turbine governor coupled to wicket gates servomotor mechanism with adjustable closing/opening times.

3. A note on water hammer modelling

Water hammer in hydropower plants can be calculated using either elastic or rigid water hammer theory [1], [9]. The elastic liquid column model is used for the systems with relatively long tunnels and penstocks, and systems with rapid transients. Slightly compressible liquid and elastic pipe walls are assumed in the elastic column model. Unsteady flow in closed conduits is described by two one-dimensional (1D) hyperbolic partial equations; the continuity equation and the equation of motion. Traditionally, the hyperbolic set of equations is solved by the method of characteristics (MOC). The MOC considers propagation of pressure waves in a physical way. There are a number of alternative solution methods for solving 1D equations [6], [9] that can be used for special cases. For transient analysis of coupled problems including hydraulic, electrical and mechanical systems electrical-analogy based method can be used [2]. For run-of-river power plants with relatively short inlet and outlet conduits the rigid column model is recommended. In this case the length of the conduit is of the same order as the cross-sectional dimensions. Incompressible liquid and rigid pipe walls are assumed in the rigid column model. Rigid water hammer is described by the one-dimensional equation of motion for unsteady pipe flow. The equation can be solved numerically by using the Runge-Kutta method. Elastic and rigid column equations are solved simultaneously with the boundary condition equations (turbine, valve, surge tank, reservoir, etc.) [1], [9].

The hydraulic turbomachine may undergo turbine, pump or pump-turbine operating modes. The governed turbine boundary condition is described by the turbine (head balance equation, dynamic equation of rotating masses) and the governor (dynamic equation which relates the pump-turbine rotational speed change to the position of the regulating mechanism(s)), and it is coupled with pipeline water hammer equations. The relationship among influential turbine variables is presented in the form of the experimentally predicted characteristics (head, torque, axial force). The complete set of the hydraulic turbomachine-governor-pipeline equations should be used for the case of load reduction in which the turbine speed is regulated by the governor. The governor equations are omitted in analysis for the case of turbine emergency-shut down in which the unit speed change is controlled by the turbine net torque only. It should be noted that 1D numerical models cannot accurately predict some high-frequency transient effects in pipelines (unsteady friction) or hydraulic turbines (draft tube vortex, rotor-stator interaction). For this case coupled 1D-3D or full 3D water hammer models have been developed [12], [13], [14]. However, modelling 3D unsteady flow problems is complicated, computationally intensive and defining the right boundary conditions in complex structures is not an easy task. Certain approximations [15], [16] may have negligible influence in particular applications but introduce significant systematic errors in other circumstances. Field test cases are needed to verify water hammer models and adequacy of design strategies.

There are a number of commercial software packages available and are adequately verified by vendors and end users. The same applies for in-house software codes. In this paper hydraulic transient analysis is performed using a basic version of the commercial computer software package SIMSEN Version 3.3.2 [7]. The software is based on a modular structure which enables the engineer to consider systems with an arbitrary topology. It is composed of objects, each representing a specific element in the network: electrical machines, mechanical systems taking into account mechanical masses, voltage supplies, transmission lines, and load controllers. Each unit includes a set of differential equations based on the network element model. A global set of differential equations is generated and solved by the fourth order Runge-Kutta procedure [2]. In order to be able to study the dynamic behaviour of a

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whole hydroelectric power plant including electrical, hydraulic and control components a hydraulic extension has been embedded in SIMSEN computer package. Hydraulic elements are modelled as RLC electrical circuits according to the impedance method [17], where 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 (R = hydraulic resistance, L = hydraulic inductance, C = hydraulic capacitance). Momentum and mass conservation equations provide the basis for an equivalent electrical circuit modelling of the hydropower system. For example the Francis turbine is modelled as a set of RLC elements. 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 steady state characteristics (hill chart). For the computation SIMSEN is using the turbine characteristics given in a form of unit speed, unit discharge and unit torque (n_{11}, Q_{11}, T_{11}). Theoretical background on electrical-analogy based method can be found in [2].

4. Water hammer analysis in Piva hydropower plant, Montenegro

This section deals with water hammer analysis in Piva HPP, Montenegro. The Piva is the peak HPP in the Montenegrin electro-energetic system with an installed capacity of 360 MVA and has been in continuous operation since 1975. The hydropower plant is located in the north-west of the Montenegro, at a distance of about 10.6 km from the location were the Tara River and the Piva River join to form the Drina River. The basin has a length of about 40 km. The dam is of concrete-arch type, 220 m high and a crest length of 268 m. Due to the need for modernization it was decided to overhaul the three vertical Francis turbine units and associated equipment with new automation system of the plant. Two units have been already modernized, the third one will be modernized early this year.

The SIMSEN computational model for Piva HPP is presented in Figure 1. The model is comprised of the intake structure, followed by three parallel penstocks each with Francis type water turbine at the downstream end. The outlet part starts with three parallel draft tubes that are connected to a common lower (downstream end) orifice type surge tank followed by tailrace tunnel and outlet structure. Each Francis turbine is connected to a mechanical system representing the influential inertia of the rotating masses (runner, shaft, generator).

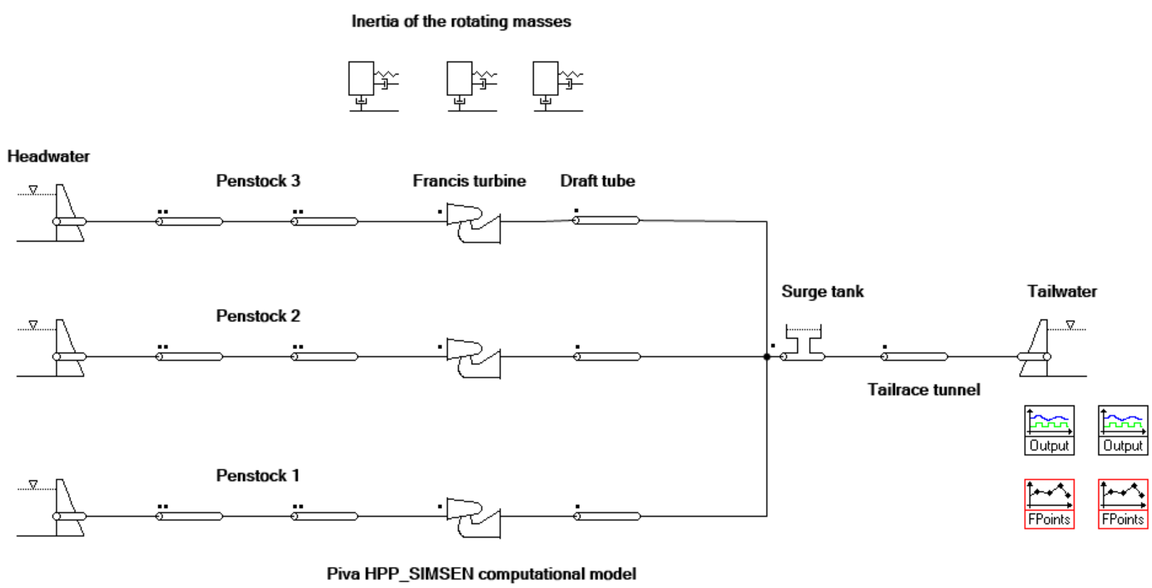

Figure 1. Layout of SIMSEN computational model for Piva HPP, Montenegro.

Each penstock is comprised of concrete and steel conduits. The length of the concrete part for penstock 1 is L = 113.32 m, for penstock 2 is L = 131.32 m and for penstock 3 is L = 147.42 m. Apart at the entrance section the diameter of the concrete conduits is D = 5.0 m. The steel part of the three penstocks is of the same dimensions i.e. length L = 150.2 m and diameter D = 4.0 m. The concrete conduit is horizontal with the axis elevation of z = 585.5 masl whereas the steel conduit is inclined with inlet axis elevation z = 585.5 masl and outlet one z = 486.5 masl. The three Francis turbines are rated to P_r = 120 MW. The rated speed of the turbine is n_r = 250 min^{-1} and the polar inertia of the unit rotating parts is $I = 1.5\times10^6$ kgm^2. Each turbine is equipped with a throughflow type butterfly turbine inlet valve with a diameter D = 3.2 m. The turbine inlet valve and the spiral casing axis are at the elevation z = 486.5 masl. The downstream end surge tank is connected to three draft tube exits and to the tailrace tunnel inlet (Figure 1). The surge tank has an ellipse-shaped compartment with cross-sectional area A = 177 m^2. The tank floor elevation is z = 483.43 masl and the crown one is z = 512 masl. There are 4 orifices at the bottom of the surge tank each of diameter D = 2.04 m. The orifice head loss coefficient is $k = 8\times10^{-5}$ m/(m^3/s)^2. The length of the tailrace tunnel is L = 110 m and the equivalent diameter is D = 11.06 m [1]. The water level in the upstream reservoir z is in the range from 595.0 masl to 677.7 masl, the level in the downstream reservoir z is in the range from 489.26 masl to 491.23 masl. The maximum allowable turbine inlet pressure head at elevation z = 486.5 masl is $H_{max,all}$ = 254.0 m and the maximum allowable turbine rotational speed rise is $\Delta n_{max,all}$ = 35%.

4.1 Measured and computed results

This section presents comparison of measured and computed results for the case of emergency shut-down (ESD) of Francis turbine in penstock 2 (Figure 1) from the maximum generating output P = 130 MW. The water levels in the upstream in downstream reservoirs were z = 672.63 masl and z = 493.34 masl. The ESD of the turbine is considered to be the most severe normal transient operating regime [1]. The turbine is disconnected from the electrical grid followed by full closure of the wicket gates (Figure 2). The closure of the wicket gates reduces the hydraulic torque, limiting the maximum rotational speed and inducing a water hammer effect in the adduction part of the flow-passage system. The resulting water hammer is controlled by the appropriate adjustment of the wicket gates closing law. In addition, the tailrace surge tank controls pressure surges in the outlet tunnel. The other two turbines increased the output to keep the plant output unchanged. Their effect was small on water level oscillations in the outlet system and can be neglected in simulations (Figure 3c). The objective of comparisons is to validate plant-system model and input data in a well verified and validated SIMSEN software package.

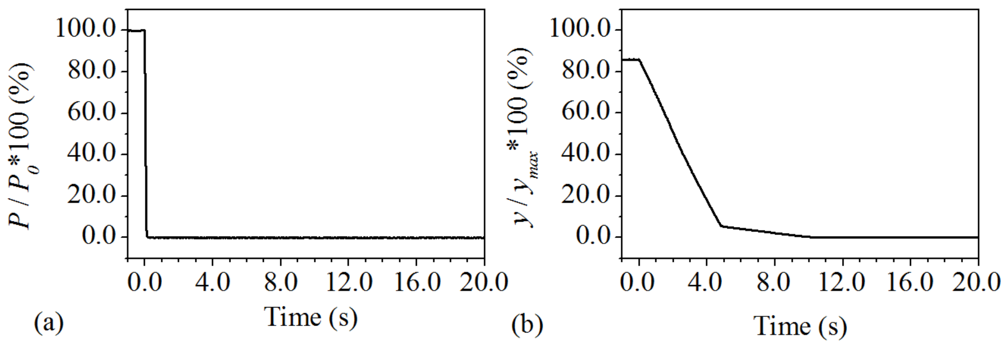

Figure 2. Measured results for the case of ESD of turbine in penstock 2: (a) generating power (P_0 = 130 MW) and (b) wicket gates servomotor stroke y.

Comparisons between measured and computed turbine rotational speed and pressure heads at the inlet and outlet of the turbine are depicted in Figure 3. The uncertainty in measurement U_x for the rotational speed is $U_x = \pm 0.1$ % and for the two pressure heads is $U_x = \pm 0.5$ %. The sampling frequency for each continuous measured signal was $f_s = 100$ Hz.

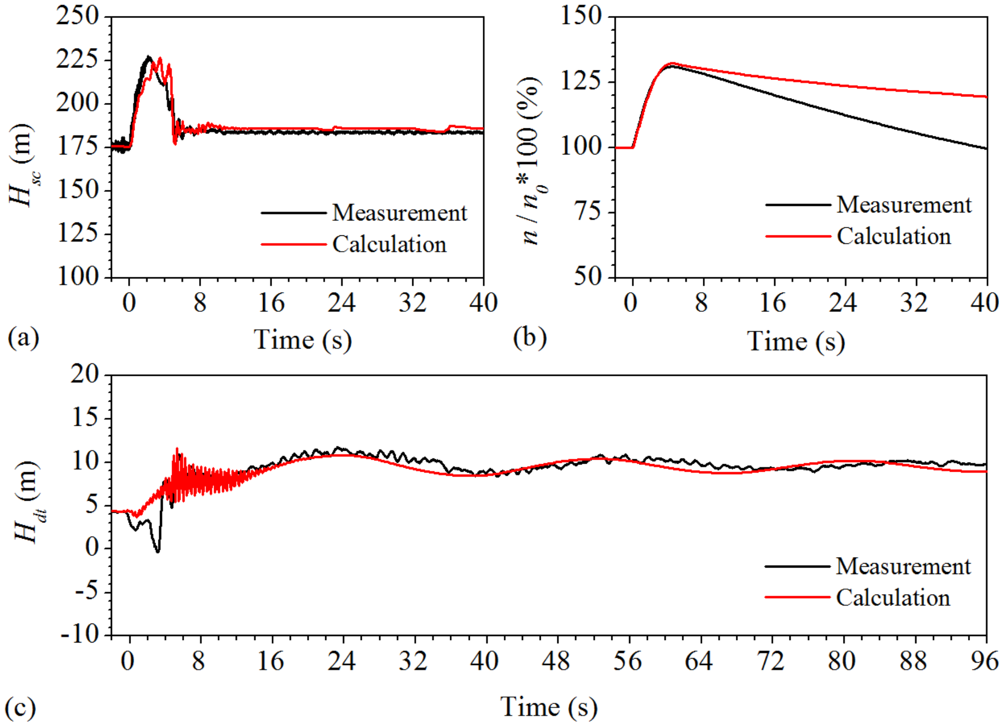

Figure 3. Measured and computed results for the case of ESD of the turbine in penstock 2: (a) turbine inlet pressure head H_{sc}, (b) turbine rotational speed n ($n_0 = 250$ min^{-1}) and (c) draft tube pressure head H_{dt}.

The maximum computed head $H_{sc,max}$ = 225.5 m (taken at elevation z = 286.5 masl) matches the measured one (Figure 2a). The maximum head is much lower than the allowed head $H_{max,all}$ = 254.0 m. There is also a good match between the computed Δn_{max} = 32% and measured maximum turbine rotational speed rise Δn_{max} = 31% (Figure 3b); both are lower than the allowed one $\Delta n_{max,all}$ = 35%. The discrepancies increase at small wicket gates openings and at closed wicket gates. The numerical model does not take into account additional dissipation due to multiphase flow structure in draft tube and other losses (bearings). Figure 3c shows draft tube pressure head H_{dt} (at elevation z = 483.5 masl) for a longer time period. The objective is to capture the effect of tailrace surge tank on attenuation of pressure surges in tailrace conduit system. The agreement between measured (averaged) and computed long-time pressure head oscillations is reasonable (at commissioning of the unit in penstock 2 the surge tank water level oscillations have not been measured). It means that the input data for surge tank model are accurate. There are some discrepancies in the early stage of the transient event that can be attributed to complex local flow behaviour in the draft tube during the closure period. The 1D numerical model cannot accurately capture multidimensional multiphase flow effects under the Francis turbine runner. The effect of exit velocity head has been taken into consideration. This topic is a subject of the authors' current research. However, the minimum measured and computed pressure heads are well above the liquid vapour pressure head. The maximum heads at the early stage of transient event are of the same magnitude as the long-time oscillating amplitude.

4.2 Computed results for simultaneous ESD of 3 turbines

Various transient regimes including ESD of one and three turbines at several headwater levels have been performed. Computed results for simultaneous ESD of all three turbines from full (100%) and partial loads (25, 50, 75%) at low headwater level z = 628.5 masl are presented in Figure 4 as an example.

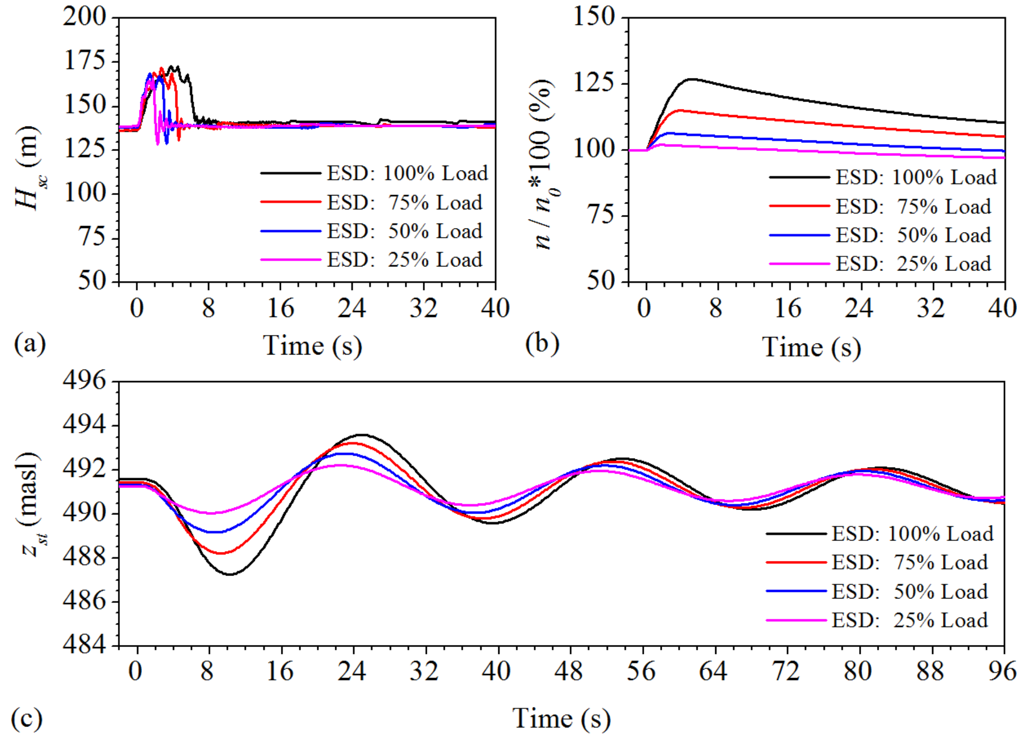

Figure 4. Computed results for the case of simultaneous ESD of 3 turbines: (a) turbine inlet pressure head H_{sc}, (b) turbine rotational speed n (n_0 = 250 min^{-1}) and (c) draft tube pressure head H_{dt}.

The objective is to show time histories of pressure head at the turbine inlet (H_{sc}), turbine rotational speed (n) and water level in tailrace surge tank (z_{st}). The wicket gates servomotor closing law is the same as the measured one at commissioning of turbine unit in penstock 2 (Section 4.1) i.e. the two-speed closing law with fast closing time T_f = 6.3 s and cushionig time T_h = 6.0 s starting at servomotor stroke y_h = 6% [18]. The extreme water hammer loads occur at full-load ESD. The maximum head at the turbine inlet $H_{sc,max}$ = 174.5 m (Figure 4a; taken at elevation z = 286.5 masl) is much lower than the allowed one $H_{max,all}$ = 254.0 m. The same holds for the maximum turbine rotational speed rise: Δn_{max} = 31% (Figure 4b) is lower than the allowed one $\Delta n_{max,all}$ = 35%. The maximum and minimum water levels in the tailrace surge tank are $z_{st,max}$ = 493.9 masl and $z_{st,min}$ = 483.7 masl, respectively (Figure 4c). The two levels are within the safe margins i.e. bellow the crown level z = 512 masl and above the tank floor level z = 483.43 masl.

5. Conclusions

Water hammer is one of the key issues in feasibility and design studies of refurbished hydropower plants. The potential increase of discharge and increased flexibility of load variations may result in much higher dynamic loads on hydropower plant components (turbine, valve, penstock) during transient operating events than for the original design. A number of water hammer control strategies are available to suppress water hammer effects that may disturb overall operation of the plant and damage the system components.

Case study of Piva HPP, Montenegro was presented in this paper. After nearly 50 years of operation a number of plant components been renovated and modernized with a particular emphasize on automation of the plant. The water hammer control devices in Piva HPP are the turbine governor coupled to the wicket gates servomotors and the orifice type tailrace surge tank. Measured and calculated results for emergency shut-down (ESD) case from maximal load agree reasonably well. However, there are some discrepancies between the two results in the early stage of the transient event. The discrepancies can be attributed to multidimensional multiphase local flow behaviour under the Francis turbine runner during the closure period. The validated RLC equivalent scheme is then used for simulation of ESDs in a wide operating range.

6. References

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