

Treatise on water hammer in hydropower standards and guidelines

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Abstract. This paper reviews critical water hammer parameters as they are presented in official hydropower standards and guidelines. A particular emphasize is given to a number of IEC standards and guidelines that are used worldwide. The paper critically assesses water hammer control strategies including operational scenarios (closing and opening laws), surge control devices (surge tank, pressure regulating valve, flywheel, etc.), redesign of the water conveyance system components (tunnel, penstock), or limitation of operating conditions (limited operating range) that are variably covered in standards and guidelines. Little information is given on industrial water hammer models and solutions elsewhere. These are briefly introduced and discussed in the light of capability (simple versus complex systems), availability of expertise (in house and/or commercial) and uncertainty. The paper concludes with an interesting water hammer case study referencing the rules and recommendations from existing hydropower standards and guidelines in a view of effective water hammer control. Recommendations are given for further work on development of a special guideline on water hammer (hydraulic transients) in hydropower plants.

1. Introduction

The role of hydropower in modern energy systems has changed dramatically in the last few decades. Nowadays hydropower is able to cover peak demands and to store surpluses of system energy, in particular that coming from intermittent generators associated with wind and solar energy. There are a number of key parameters associated with the design of a new or aging hydropower plant (refurbishment and upgrading) including safety, efficiency, availability and profitability of the plant. While there is certainly room for further improvements when designing new plants, this is seldom the case for refurbishments, in particular, severe constraints hold for the civil facilities (tunnel, surge tank, penstock). The refurbishment may include overhaul or replacement of some critical components of the turbine unit and water conveyance system or installation of completely new components (pressure regulating valve). The enhancement of the plant output may be achieved by increasing either the turbine efficiency or the discharge. The increase of discharge and flexibility of load variation may result in much higher dynamic loads on refurbished and non-refurbished plant components during transient operating events (rapid load acceptance and reduction, load rejection, emergency shutdown) than the original design [1]. These might be large pressures in system components (penstock, turbine), excessive turbine rotational speed, water column separation and distributed cavitation due to low pressures, excessive vibrations and strong



oscillations or/and water masses in the fluid-conveyance system (basin-headrace tunnel-surge tank). Traditionally the most important calculated quantities that should be guaranteed are the maximum and/or minimum momentary pressure at the turbine inlet and/or outlet and the maximum unit rotational speed rise [2], [3], [4], [5]. The guaranteed quantities are compared with field-test results during commissioning; results should show adequate agreement where it is not possible to perform tests under specified conditions [4]. Recommended maximum turbine rotational speed rise during load rejection is 60% [6], [7]; however, in special cases a larger maximum speed rise might be permitted. In general, there is no specified limit for the maximum transient pressure in fluid-conveyance systems. Safety, economic and operating conditions together determine the maximum allowable transient pressure. It is recommended that the minimum transient local pressure in any conduit should not drop below 50 kPa (equivalent pressure head of 5 m) [7] in order to avoid the danger of water column separation (or of pipe collapse) and consequently large pressure loads due to cavity collapse [8]. The water hammer analyst should be able to assess safe and economic operation of the plant during water hammer events. The analyst should be able to identify critical transient regimes and consequently to design appropriate water hammer control strategies.

The main objective of this paper is to summarize, discuss and assess a treatise on critical water hammer parameters in a light of official hydropower standards and guidelines. Pejović *et al.* [7] have proposed six parameters that somehow characterize transient regimes in a particular hydropower plant i.e. water starting time, unit starting time, penstock reflection time, theoretical period, period of mass oscillations and the Joukowsky pressure head. These parameters are briefly addressed also in IEC 60308 [5]. A particular emphasize is given to a number of IEC standards and guidelines that are used worldwide. Hydraulic vibrations (draft-tube surge, rotor-stator interactions, auto-oscillations) [9], [10], [11] and transients in open channels [12], [13] are beyond the scope of this paper. The coverage in reference books is briefly introduced. The paper critically assesses water hammer control strategies including operational scenarios (closing and opening laws), surge control devices (surge tank, pressure regulating valve, flywheel, etc.), redesign of the water conveyance system components (tunnel, penstock), or limitation of operating conditions (limited operating range) that are and some are not covered in standards and guidelines. As little information is given on industrial water hammer models and solutions elsewhere, these are briefly discussed in the light of capability (simple versus complex systems), availability or expertise (in house, commercial) and uncertainty. The paper concludes with an interesting water hammer case study referencing some of the rules and recommendations from existing hydropower standards and guidelines in a view of effective water hammer control. Recommendations are given for further work on development of a special guideline on water hammer (hydraulic transients) in hydropower plants.

2. Water hammer control strategies

Excessive transient loads may disturb the overall operation of a hydropower plant and damage system components. In particular, the increase of discharge and flexibility of load variation in a refurbished plant lead to much higher dynamic loads on both refurbished and non-refurbished plant components during transient operating events (rapid load acceptance and reduction, unit shutdown) than anticipated during the original design. Water hammer analysis has to be performed for a range of initial steady state operating conditions including conditions with both maximum and minimum heads, and discharges. The scope of water hammer analysis clearly depends on the type of machine and complexity of the plant layout as well as on the stage of the design process (feasibility, new design, commissioning, rehabilitation, trouble-shooting). Classical water hammer analysis traditionally includes the following normal, emergency and catastrophic reaction turbine operating regimes [7], [13], [14], [15]:

(i) Normal operating regimes

- turbine start-up (the unit is started from standstill to speed-no load),
- load acceptance,

- load reduction,
- normal shutdown of the unit,
- sudden load rejection,
- shutdown under governor control (normal closure),
- emergency shutdown (mechanical/electrical quick stop).

(ii) Emergency operating regimes

- partial turbine runaway,
- emergency shutdown (for example inoperative runner blades in a double-regulated Kaplan turbine).

(iii) Catastrophic operating regimes

- maximum turbine runaway,
- earthquake.

In pump-storage plants hydraulic transients in pumping mode of operation should be investigated too. On top of this, the unit might operate in synchronous compensation mode. Pejović *et al.* guideline [7] presents a number of normal, emergency and catastrophic transient regimes including operation of various turbines (Francis, Kaplan, Pelton), pump-turbines (Francis, Kaplan), pressure regulating valves, shutoff valves and gates. It is recommended that analysis includes cases with extreme values of discharge and head when either one unit or all units operate, cases with malfunction of one of the devices (inoperative guide vane apparatus) and cases with unfavourable sets of events. Water column separation and resonance should be avoided in fluid-conveyance systems whenever possible. Runaway tests should be performed only if this is contractually required; these tests shall be time limited [1], [16]. IEC 62006 [16] recommends emergency shutdown to be performed first due to safety reasons. IEC 61308 [5] and IEC 61236 [17] recommend performance of the following safety tests: unit trip (rapid shutdown), emergency shutdown, testing of over-speed safety device and checking interlocks. IEC 60545 [2] clearly describes the importance and extent of adequate performance of water hammer tests in the phase of commissioning, operation and maintenance. Load rejection tests should be performed at successively higher loads up to the maximum expected load. After each load rejection test, the pressure rise and the turbine speed rise data should be analysed to ensure that prescribed limits will not be exceeded during the next higher load rejection test. Finally, IEC 61362 [17] states that terms for operational transitions (transient operating regimes) cannot be standardized at the time being because the terms are used differently and contradictory today in the international community. There is a strong need to harmonize and standardize terminology in a new hydropower guideline on water hammer in the near future.

Water hammer in the hydropower system [5], [7], [13], [17], [18], [19] can be kept within the prescribed limits (e.g., pressure in the flow-passage system, turbine rotational speed, surge tank water level, etc.) with one or with combination of two or more of the following methods:

(i) Alteration of operational regimes includes appropriate regulation of the wicket gate and runner blade manoeuvres in reaction turbines, and turbine distributor (needle valve) and jet deflector manoeuvres in impulse turbines. Typically a two-speed wicket gate closing time function (adding a cushioning stroke) significantly improves reaction turbine safe operation. Opening of runner blades during Kaplan or bulb turbine shutdown (normal, mechanical quick stop, emergency closure) results in favourable blade manoeuvring, improved over-speed performance and reduced negative axial hydraulic thrust [20]. Programmable gate closure with the aid of pressure following-up device [21] results in reduced maximum conduit pressure. In addition, appropriate setting of closing/opening times of the shutoff valves contributes to safer operation of these devices in emergency and exceptional operating conditions.

(ii) Installation of surge control devices in the system to alter the system characteristics (shorten the active conduit length, reduce the effects of liquid compressibility, increase the turbine inertia). The

protective devices that may be installed along the inlet and outlet conduit or added to the hydropower system components include:

- increased turbine unit inertia (adding flywheel to small units, increasing the generator inertia);
- resistors (to absorb excessive power);
- 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);
- pressure-regulating valve (operates synchronously with the turbine guide vane mechanism);
- pressure-relief valve (opens at a set pressure, small units) or rupture disc (bursts at a set pressure, small units), except where an altered access environment prevents continued use of these;
- 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.

(iii) Redesign of the flow-passage system layout includes:

- change of the conduit profile (high point) and dimensions (diameter, length);
- different position of the system components (valve).

As an alternative IEC 60308 [5] and IEC 61362 [17] classify safety devices (unit shutdown, over-speed protection device, interlocks) and supplementary equipment (by-pass valve, sluicing operation, resistors) for water hammer control. Anyhow, safety, operational and economic issues are decisive for selection of the adequate water hammer control devices. A number of alternatives should be investigated before the final design that may include a combination of various design strategies. This is somehow straightforward task in the design of a new hydropower plant. On the other hand, it is rarely feasible to redesign the existing flow-passage system in the case of refurbishment and upgrading of the plant. It is usually hard to install additional surge control devices in the system except in some cases to increase the turbine unit inertia. However, it is highly probable that any existing control device will need rehabilitation to a degree similar to the turbine unit itself [1]. The most convenient water hammer control method in case of refurbishment and upgrading of the plant is typically the alteration of operational regimes. However, the rehabilitation process offers the advantage of allowing comparative water hammer tests in the plant before and after the rehabilitation; the design of the new plant is based on a gained knowledge and good engineering practice.

3. Water hammer software models

Water hammer analysis is traditionally undertaken with deterministic models [13], [18] that treat a number of transient regimes based on experience, guidelines and codes. In addition, parametric analysis accounts for uncertain parameters (e.g., friction, wave speed). These results form the basis for risk analysis to transients in hydropower plant that includes identification of critical regimes, evaluation of the risk (low, high) and risk management (modifications to reduce the risk) [22]. However, any deterministic approach resists deeper probabilistic interpretation. A stochastic water hammer model has been recently introduced [23] that at least theoretically covers system conditions and uncertainties. To account for uncertainties Pejović and co-authors [7] recommend that a shortened time of 90% of the full speed stroke should be used when maximum transient pressures are investigated. On the other hand, a prolonged time of 110% of the full speed stroke should be used when one calculates the maximum transient speed rise. The authors suggest that the difference between the measured and the computed values should not be greater than 5%, or for less accurate analysis greater than 10% of the maximum value. Water hammer analysis in a refurbished plant should be always based upon recent measurements on transient loads (pressure rise, speed rise) to be sure that changes in design and hydraulic characteristics are adequately taken into account. In any case, water hammer analysis should be performed in the design stage for a new or refurbished plant [1]. The analysis plays a vital role in mechanical integrity assessment and improved performance of the turbine unit. 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. Hydropower standards and guidelines traditionally do not provide details on water hammer models, and only a terse overview on modelling and simulation is given in IEC 61362 [17] and by Pejović *et al.* [7]. This is not the case in water supply industry. DVGW W 303 code of practice [24] provides more detailed review on fundamental physical principles and methods for water hammer analysis. The code also includes description of water hammer control strategies and to a lesser extent field test procedures. The last two are well covered in hydropower standards and guidelines.

It should be noted that in addition to the widely accepted and applied physical measurement uncertainties [25] in hydropower industry (in particular power, discharge, specific hydraulic energy, efficiency) [4], there are also corresponding uncertainties associated with the results obtained from the numerical/mathematical model which must be taken into account in evaluating any comparison [26]:

- a) systematic uncertainties inherent to the mathematical model and its solution;
- b) errors due to defects in the coding of the model;
- c) systematic uncertainties arising from the user's application of the code; and
- d) systematic and random uncertainties in the physical data supplied to the code.

Any mathematical model consists essentially of three elements:

- a) mathematical descriptions of the physical system and its boundary conditions;
- b) analytic and numerical procedures applied to these to produce a solution or approximation; and
- c) coding of the equations and solution procedures into software package.

The mathematical description of the physical system invariably introduces assumptions and approximations which may have negligible influence in certain applications but introduce significant systematic errors in other circumstances, for example application of either *rigid column* or *elastic column* water hammer model [27]. *Mathematical description* of the system is then adapted into the form of a *numerical solution* (some form of numerical integration procedure) and coded into a *software package*. Test cases are often used to verify software, which includes the simple issue of whether there are errors in the coding itself, as opposed to the underlying model and solution method. In applying the code the end user has to make decisions which may influence the success or otherwise of the validation comparison. For any specific case study, having decided on the description of the system the user should supply the numerical data which defines that model as corresponding to the physical system under consideration (pipe lengths, cross-sectional areas and friction factors, fluid properties, boundary condition and device properties or characteristics (turbine hill chart), valve closure times, etc.). All of this data is measured and is therefore subject to uncertainty which propagates into any solution [26]. IEC 60308 [5] only briefly addresses inaccuracies due to input data and due to computing program whereas IEC 60041 [4] recommends tolerances for pressure and speed variations in a light of guaranteed values.

4. Case study: Water hammer in Kaplan turbine hydropower plant

This case study presents an example of parametric water hammer analysis in a Kaplan turbine hydropower plant Zlatoličje on the Slovenian part of Drava River. Zlatoličje HPP has been recently refurbished and upgraded. The flow-passage system of Zlatoličje HPP is shown in figure 1. Two Kaplan units are embedded into an open channel system. The length of the inlet channel is of 17,200 m and the outlet channel is 6,200 m long. The channels are of trapezoidal profile with its bottom and side walls concrete lined. The dimensions of the inlet conduit and scroll casing, and the draft tube are expressed as the geometrical characteristics G_u and G_d [28], respectively (figure 1). The assumed flow-passage system used for water hammer analysis is comprised of relatively short inlet (scroll case: 60% of G_u) and outlet (draft tube) conduits. The polar moment of inertia of the generator is $I = 3.375 \times 10^6 \text{ kg m}^2$. Each of the two turbines is equipped with a pressure regulating valve (PRV). The PRV comprises five vertical vanes

connected via the rod to the servomotor and controlled by the turbine governor. During the transient operating regime the pressure regulating valve is designed to attenuate free surface waves in the inlet and the outlet channels. The continuous measurements of the channel water levels at the turbine inlet and outlet have indicated that water level oscillations in the two open channels are small and within the prescribed limits during transient events [29]. 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 both channels is beyond the scope of this paper. Water hammer in the inlet and outlet conduits is controlled by appropriate adjustment of the guide vanes and runner blades closing/opening manoeuvres. The turbine inlet and outlet conduits are relatively short; the length of the conduit is of the same order as the cross-sectional dimensions. The wave reflection times in liquid flow are indeed very short. In this case the standard one-dimensional elastic water hammer model cannot accurately predict the physics of wave transmissions and reflections [27]. The rigid water hammer model is recommended to be used for this case. Incompressible liquid and rigid pipe walls are assumed in the model [18], [28].

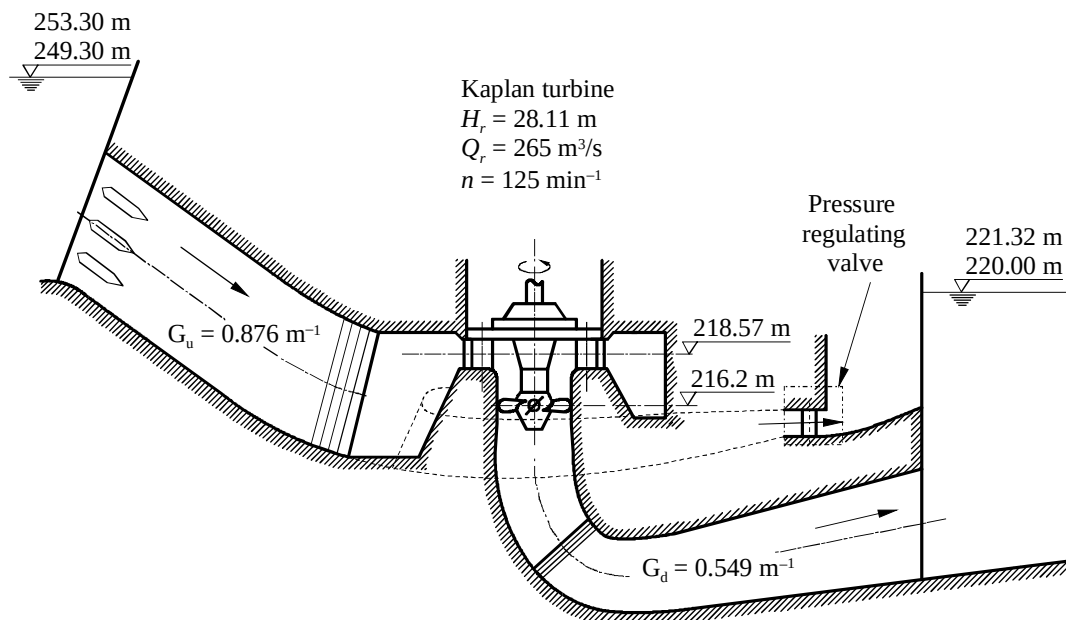


Figure 1. Zlatoličje HPP flow-passage system [29].

Water hammer analysis in the final design stage of Zlatoličje HPP was performed for a number of normal, emergency and catastrophic operating regimes [7], [13], [14]. Normal operating regimes include the turbine start-up, load acceptance, load reduction, normal shutdown of the unit, load rejection under governor control, and emergency shutdown (mechanical/electrical). Emergency operating regimes occur when one of the pressure control devices encounters malfunction. Partial turbine runaway and emergency shutdown (with inoperative runner blades) operating regimes have been calculated. Analysis of catastrophic operating regimes includes turbine runaway (on-cam initial conditions) and maximum turbine runaway (off-cam initial conditions). The rigid water hammer model results in Zlatoličje HPP have been previously validated by prototype measurements in our IAHR Symposium paper in Beijing [29]. The differences between the calculated and measured values were within the recommended margins [7].

The objective of this paper is to present calculated results as suggested in Pejović *et al.* guideline [7]. As previously stated the authors recommend that a shortened time of 90% of the full speed stroke should be used when maximum transient pressures are investigated. On the other hand, a prolonged time of 110% of the full speed stroke should be used when one calculates the maximum transient speed rise. Emergency shutdown of the Kaplan turbine unit is considered to be one of the most severe normal operating regimes

with respect to large transient pressure heads, turbine rotational speed, axial hydraulic thrust and surges in open channels in general. The turbine is disconnected from the electrical grid followed by the complete closure of the guide vanes while the runner blades open to their fully open position. 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 of $t_{c, PRV} = 1200$ s is long enough to keep water level oscillations in the two open channels within the prescribed limits during the transient event [29]. Figure 2 shows guide vane and runner blade full servomotor strokes with shortened (−10%), basic and prolonged (+10%) times for the considered emergency shutdown operating regime. According to the IEC 60308 definition [5], the corresponding basic closing and opening times are as follows:

- guide vane rapid closing time $T_{f,gv} = 10$. s
- guide vane cushioning time $T_{h,gv} = 15$. s
- guide vane cushioning servomotor stroke $y_{gv,h}/y_{gv,max} = 0.15$
- runner blade opening time $T_{g,rb} = 30$. s

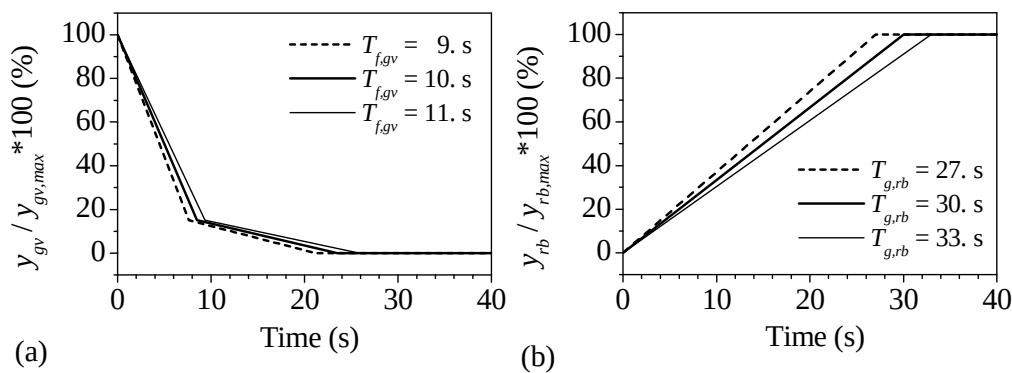


Figure 2. Guide vane (a) and runner blade (b) servomotor strokes.

Figure 3 shows results of rigid water hammer analysis for the emergency shutdown of the unit from the maximum load of 80 MW. The corresponding unit starting time is $T_a = 7.4$ s and the inertia water time constant is $T_w = 0.9$ s. The results are presented for shortened, basic and prolonged guide vane closing times at constant basic runner blade opening time of 2.3 s. Due to the rapid opening time (large initial runner blade opening) the results using shortened, basic and prolonged opening times are practically the same when using the three guide vane closing times. The computed maximum momentary scroll case pressure head ($H_{sc,max}$) for shortened, basic and prolonged guide vane closing times is 36.7 m, 36.5 m and 36.3 m, respectively (figure 3(a)). The influence of the guide vane closing time change of $\pm 10\%$ on the maximum scroll pressure is practically negligible i.e., $\pm 0.5\%$. The minimum momentary scroll pressure of 32.7 m is the same for the three cases considered. The computed maximum momentary draft tube pressure head $H_{dt,max} = 7.2$ m is the same too. There are relatively small differences for the minimum draft tube pressure head of 2.4 m, 2.5 m and 2.6 m, respectively ($\pm 4\%$). This is not the case for the maximum momentary turbine rotational speed rise of 28.1%, 29.5% and 30.9% (figure 3(c); $n_0 = 125 \text{ min}^{-1}$) which gives larger differences i.e. $\pm 5\%$. This difference might be important when we need to fulfil guarantees according to IEC 60041 [4]. In our case, the maximum scroll case pressure head and the maximum speed rise are within the prescribed limits for all the cases considered. Another important quantity that is not explicitly addressed in IEC standards and guidelines is the negative axial hydraulic thrust which may cause lifting of the turbine unit. The calculated maximum momentary negative axial hydraulic thrusts (absolute values) of 3960 kN, 3860 kN and 3770 kN, respectively are less than the permissible axial thrust $|F_{a,max}^-| = 5370$ kN (figure 5(d); $F_{a,0}^+ = F_{a,0} = 5800$ kN). The maximum positive axial hydraulic thrust is the initial axial thrust of 5800 kN.

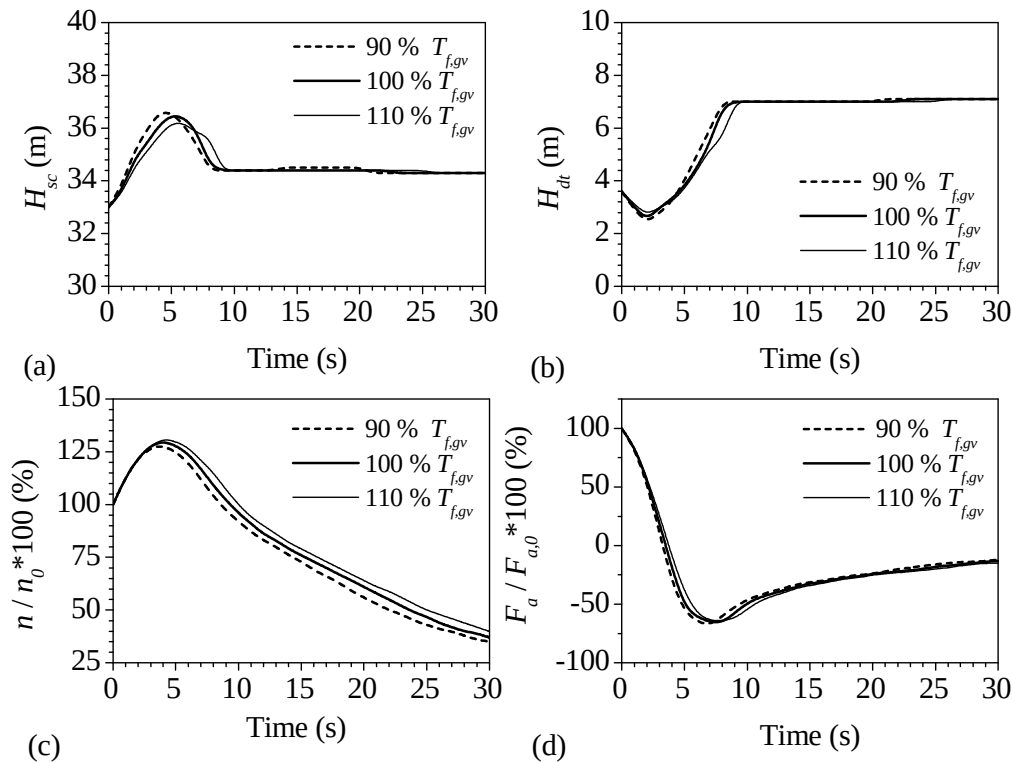


Figure 3. Emergency shutdown in Zlatoličje HPP ($P = 80$ MW; $y_{gc,0} = 92.4\%$; $y_{rb,0} = 92.5\%$; $T_{g,rb} = 0.075 \times 30$. $s = 2.3$ s = const): Scroll case (a) and draft tube (b) pressure heads, unit rotational speed (c) and axial hydraulic thrust (d).

5. Conclusions

This paper presents a treatise on critical water hammer parameters in a light of official hydropower standards and guidelines. A particular emphasize is given to a number of IEC publications that are used worldwide. Water hammer control strategies may traditionally include operational scenarios (closing and opening laws), surge control devices (surge tank, pressure regulating valve, flywheel, etc.), redesign of the water conveyance system components (tunnel, penstock), or limitation of operating conditions (limited operating range). Alternatively IEC 60308 [5] and IEC 61362 [17] treat safety devices (unit shutdown, over-speed protection device, interlocks) and supplementary equipment (by-pass valve, sluicing operation, resistors) for water hammer control. These two publications recommend performance of the following safety tests: unit trip (rapid shutdown), emergency shutdown, testing of over-speed safety device and checking interlocks. IEC 60545 [2] describes the importance and the extent of adequate performance of water hammer tests in the phase of commissioning, operation and maintenance. Moreover, IEC 61362 [17] states that terms for operational transitions (transient operating regimes) cannot be standardized at the time being because the terms are used differently and contradictory today in the international community. Industrial water hammer models and solutions are briefly introduced and discussed in the light of capability (simple versus complex systems), availability (in house, commercial) and uncertainty. Hydropower standards and guidelines traditionally do not provide details on water hammer models, only an abbreviated overview of modelling and simulation is given in IEC 61362 [17] and by Pejović *et al.* [7]. IEC 60308 [5] briefly addresses inaccuracies due to input data and due to computing program whereas IEC 60041 [4] recommends tolerances for pressure and speed variations in a light of guaranteed values. The paper provides a water hammer case study referencing the

rules and to illustrate the recommendations arising from existing hydropower standards and guidelines with a view of achieving effective water hammer control.

There is a strong need for further work on development of a special guideline on water hammer (hydraulic transients) in hydropower plants which would bring together pieces from existing standards and guidelines. There is a strong need to harmonize and standardize terminology for water hammer control strategies and transient operating regimes. Much more detailed review on fundamental physical principles and methods for water hammer analysis should be included in the new standard as well. The question is posed whether to include hydraulic vibrations and open channel surge issues in the new guideline too. The Guidelines [7] includes hydraulic vibrations and should be further updated to inform businesses and decision makers that not only water hammer but also vibrations and particularly resonance could be exceedingly dangerous.

6. References

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