Numerical Analyses of Water Hammer and Water-Mass Oscillations in a Hydropower Plant for the Most Extreme Operational Regimes

Jovan Ilić
PhD Student
University of Belgrade
Faculty of Mechanical Engineering

Aleksandar Petković
Hidromaškonsalting, Belgrade

Ivan Božić
Associate Professor
University of Belgrade
Faculty of Mechanical Engineering

Hydraulic transients analyses are necessary during the design stage of both new and refurbished hydropower plants (HPPs). In this paper, transients of specified most extreme operational regimes are investigated for a long derivation system, provided with a surge tank as well as pressure relief valves (PRVs) at the turbines spiral casing. The transients analyses are focused on water-mass oscillations and water hammer. Investigations for various exploitation regimes and different operating laws of the PRV's are adopted. Results are obtained by means of an original software developed for these analyses. The model was duly calibrated, and the results were compared with the results of the transient analyses from the original design phase of the existing HPP.

Keywords: *hydraulic transients, water hammer, water-mass oscillations, hydraulic turbines, surge tank, pressure relief valves.*

1. INTRODUCTION

Energy presents one of the basic factors that describe the wealth of a nation and it would not be an overstatement that the power of a country depends on quantity and quality of its own generated energy. Modern society gave focus to renewable energy sources as hydro, wind, solar etc. Out of all renewable energy sources being harnessed, hydropower is the most precious one. Hydropower plants (HPPs) are characterized by their operating flexibility, high-efficiency performance and reliability. Volatile energy generation demands require HPPs to change their operating regimes frequently. Such changes have influence on water-mass oscillations (WMOs) in the derivation system and are manifested by discharge, pressure and surge tank water elevation variations. Hydraulic transients analyses are necessary during the design stage of both new and refurbished hydropower plants [1]. Complexity in mathematical models requires appropriate numerical solvers for their implementation [2-7]. In general, transients analyses can be done in multiple ways depending on a type of problems under investigation. In Table 1, a general overview of the groups of analyses is shown [8]. Results presented in this paper are acquired by using original software that has been developed [9] for the research of water hammer (WH) and WMO transients in HPPs.

WH and WMO (as well as TGOV) require one the same mathematical model of the entire HPP (from headrace to tailrace, including waterways, generating equipment and protective devices), whereas the analyses are performed in time (t-) domain.

Table 1. Types of transient analyses in HPP

No	Analysis	Explanation
	WMO	Water-mass oscillations. These analyses (in t-domain only) are performed if there is a surge tank within HPP. These transients are manifested by low-frequency pressure and discharge oscillations in the low-pressure part of the derivation system (reservoir – tunnel – surge tank).
	WH	Water hammer. These transients are manifested as violent pressure and discharge variations in the high-pressure part of the derivation system (surge tank – penstock – turbine). These analyses (in t-domain only) are performed so to investigate transient behaviour of the penstock system and the turbines.
	TGOV	Turbine governing. These analyses (in t- or in frequency (f-) domain) are performed so to determine turbine governor settings and determine HPP load manoeuvrability while operating on electric power network in the modes of power- or frequency regulation (P-governing or f-governing).
	HOSC	Hydraulic oscillations. These analyses (usually just in f-domain) are performed within investigation of possible resonance under steady-oscillatory operation of HPP.
	OPCH	Open channel unsteady flow. These analyses (in t-domain only) are performed if HPP avails with an open channel within the conveyance waterway.
	LGOV	Level governing. These analyses are required for the HPPs that adjust operating discharge as per river inflow or operate within cascades with the relatively small reservoirs. These analyses (in t- or in f-domain) are performed so to determine turbine governor or HPP joint-controller settings (l-governing).

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Correspondence to: Ivan Bozic, Ph.D.ME
Faculty of Mechanical Engineering,1
Kraljice Marije 16, 11120 Belgrade 35, Serbia
E-mail: ibozic@mas.bg.ac.rs
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Adequate investigation approach requires insepa–rable, combined treatment of WH and WMO. Otherwise (simplified WMO models of HPPs that are limited just to the low-pressure part of the derivation system and encounter only the effects of discharge variations coming from the high-pressure part, excluding pressure variations and invasive influence of the pressure waves protruding in the low-pressure part), results significantly deviate. Such simplifications are particularly inadequate for the HPPs availing with long tailrace derivation waterways (safety against minimum head envelope, water-column separation and reverse water-hammer problem).

This paper presents results of the WH and WMO simulations which are done during analyses of transients for the most extreme operational regimes in an existing HPP. The original software is adjusted so to depict all the elements of the considered HPP.

2. THEORETICAL BACKGROUND AND MATHEMA–TICAL MODELLING

Water hammer and water-mass oscillations analyses demand expertize knowledge of fluid mechanics with special attention to unsteady fluid flow phenomena, as well as mathematical modelling and computer skill for their implementation. Equations that describe these phenomena can be solved just numerically. The ones that are used are basic equations of fluid mechanics – continuity equation and dynamic equation, and boun–dary conditions depending on a system that is investi–gated. Along with the boundary conditions, the Method of Characteristics for solving unsteady states within pipe reaches interior [9,10] is highly recommended as the mostly used implementation method. With appli–cation of the Method of Characteristics, equations (1) and (2) are aquired[2]:

$$Q_p = C_p - C_a \Pi_p \tag{1}$$

$$Q_p = C_n + C_a \Pi_p \tag{2}$$

where Q is discharge and Π is piezometric head, wheras P represents their unknown values for the on-going time layer. These relations are transformed into normal diffe–rential equations that may be used for numerical simu–lations. Coefficients C_p, C_n and C_a are defined as [2]:

$$C_p = Q_A + \frac{gA}{a}\Pi_A - \frac{\lambda \Delta t}{2DA} Q_A \left| Q_A \right| \tag{3}$$

$$C_n = Q_B + \frac{gA}{a}\Pi_B - \frac{\lambda \Delta t}{2DA} Q_B \left| Q_B \right| \tag{4}$$

$$C_a = \frac{gA}{a} \tag{5}$$

where A is the cross-section area of the pipe, a is the wave velocity, D is the diameter of the pipe, λ is the friction coefficient and Δt is the time step. Selection of the time step value should be in line with the criteria of numerical stability. Indices A and B relate to the quantities already known from the previous time layer. Equations (3) and (4) use first order approximation of the energy losses term, which is satisfactory for most problems (except the class where friction term dominates [3]). Method of Characteristics is commonly used in the engineering calculations because of its sim–plicity and satisfactory precision, although lately more complex implementation schemes are becoming ava–ilable, being very efficient and better representing phy–sics of the phenomena [11], but requiring more compu–tation time for the process simulations. Mathematical modelling of the boundary conditions is always up-to-date topic, especially when delivering new technical so–lutions which should be numerically described. The friction coefficient is modelled as steady-friction and keeps fixed value for a defined section over the endu–rance of the simulated process. Moreover, it is calcu–lated by means of one of the explicit approximations of Colebrook-White equation. More accurate approxima–tions of Colebrook-White equation are still being deve–loped [12,13]. In certain cases, unsteady friction models [14-17] may be of better use, notwithstanding their modelling complexity and computation requirements as implementation drawbacks.

3. SIGNIFICANCE OF WATER HAMMER AND WATER-MASS OSCILLATIONS ANALYSES

Water-mass oscillations analyses are used to investigate unsteady phenomena in the low-pressure part of the waterway conveying system of the derivation-type HPPs provided with surge tanks. This part stretches from the upper reservoir to the surge tank and is cha–racterized by low-frequency, slow-changing hydraulic oscillations. The main purpose of WMO analyses is to appropriately select constructive- (surge tank location, type and parameters) and regime-type (manoeuvring laws) protective measures. In case of a newly designed HPP, it is very important to define the optimal surge tank location, type and parameters [18-20] not only from a standpoint of plant safety, but also from the standpoints of economy and functionality. Main para–meters of these analyses are surge tank water level (ST_{WL}), discharge upstream of the tunnel (Q_{ups}) and discharge through stand pipe that connects surge tank with the derivation system (Q_{sp}). The surge tank is one of the most expensive protection issues during const–ruction of a HPP.

Water hammer analyses are used to investigate un-steady phenomena in the high-pressure part (surge tank – penstock – turbine) of a HPP waterway system. WH is investigated in the section from the surge tank to the turbine if the system is equipped with a surge tank, otherwise, these analyses relate to the entire derivation system (headrace reservoir to turbine). The main pur–pose of WH analyses is to appropriately select cons–tructive- (for newly designed HPPs – penstock sections diameters and path, flywheel of the gen-unit etc.) and regime-type (turbine wicket-gate closing law - WG_{ML}, pressure relief valve manoeuvring law - PRV_{ML}, etc.) protective measures. WMOs being slow oscillations are investigated over a relatively long period (a few minutes or tens of minutes). WH is investigated over a shorter time-frame (up to a few tens of seconds). Parameters subject to analyses are turbine revolving speed (*TRS*), spiral casing head (*SCH*), head envelopes in the derivation system (minimum - H_{min}, maximum - H_{max}, steady state - H_{st}) along the waterway path (*WP*). As previously mentioned, WMO and WH are investigated by the same mathematical model, whereas the dif–ference is just in the nature of these two processes, du–ration, issues that are investigated and protective measures that should be adopted. It is very important to examine situations in which particular safety elements unexpectedly failed. This kind of research is significant because it presents real-time situations that could occur during HPP exploitation. It is obvious that safety elements are built to prevent system from overloading in various exploitation regimes. For WMO comparative analyses, the HPP design documentation [21] is ac–quired and used for comparison of simulation results, calibration and validation. The extreme regimes from the standpoint of WMO, i.e. turbines load-rejection, start, quick shut-down (load-rejection recently after start - QSD) and quick-restart (start recently after load-rejection - QRS) are investigated and compared. For the WH extreme situations analyses, pressure relief valves malfunctions are taken into account along with different closing laws of wicket-gate (comprehensive sensitivity analyses of the output results into the values of the input parameters).

4. CASE STUDY

In order to do essential analyses and obtain necessary results, HPP Pirot was chosen as a representative of a very complex system. HPP Pirot is located in the south-east of Serbia. Reservoir is the lake of "Zavoj", at the altitude of 600 masl. Tailwater elevation varies insigni–ficantly, and is approximately 370 masl. Water is deli–vered to the powerhouse via the derivation tunnel length of over 8 km and approx. 2 km of penstock. The two Francis turbines are of the following characteristics each: rated output 40 MW, synchronous speed of 500 rpm and maximum discharge of 22.8 m^3/s. The HPP is equipped with many safety elements as it is shown in Fig. 1. Both turbines (T1 and T2) avail with pressure relief valves (PRV1 and PRV2), being placed at spiral casings.

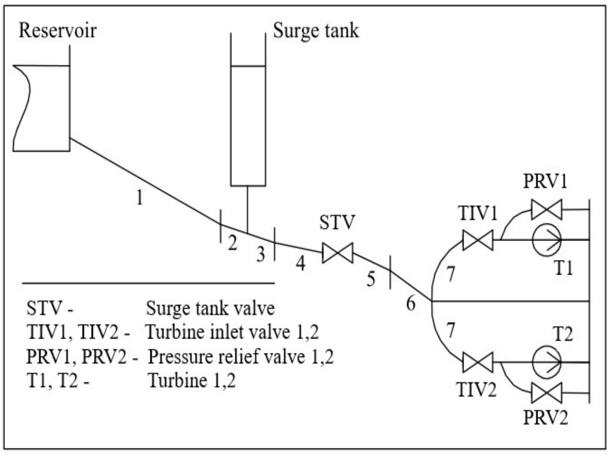

Figure 1. Hydropower plant Pirot scheme

For every section of the water-conveying system, characteristic parameters were acquired (Tab. 2). Surge tank comprises shaft of 16 m diameter and the two chambers (upper and lower). Surge tank is connected to the main waterway by a lateral standpipe. Wave velocity is calculated between 1270 m/s and 1300 m/s in tunnel reach and 800 m/s to 950 m/s in the penstock reaches. Characteristic water elevations of the upper reservoir are as follows: minimum level 568 masl, maximum operating level 615 masl and spill-over level 617.3 masl. Surge tank valve is a butterfly valve of 3000 mm diameter.

Table 2. Characteristic parameters of delivery system

Part	Length L [m]	Diameter D [mm]	Friction coefficient λ [/]	Remark
1	8551	4500	0.016	Tunnel
2	60	3800	0.016	Tunnel
3	80	3800	0.016	Tunnel
4	390	3700	0.016	Tunnel
5	700	3500	0.011	Penstock
6	757	3300	0.011	Penstock
7	20	1700	0.011	Penstock

PRVs are usually coupled with the wicket gate of a hydraulic turbine, which means that law of PRVs opening stroke is complementary to the turbine wicket-gate closing stroke. PRVs are needle type valves of 800 mm diameter. All elements presented in Fig.1 are mathematically modelled as boundary conditions and used within the program for numerical simulations of transients.

Acceptance criteria (a.c.) for the analysed parame–ters are:

$$ST_{WL,\max,a,c} \,/\, ST_{WL,\min,a,c} = 630.8 / 546.0 \; [m]$$
$$TRS_{\max,a,c} = 675 \; [rpm]$$
$$SCH_{\max,a,c} = 302.9 \; [m]$$

Expected maximum pressure at the downstream end of the tunnel is 8 bar.

4.1 Overview of the analysed operational regimes

Comprehensive WMO and WH analyses are performed and various cases of extreme situations are presented. The operational regimes that are analyzed in this paper are defined in Table 3, along with the initial steady-state conditions. WMO analyses comprise investigations of the SD, $START_{SMS}$, QSD_{SMS} ($START_{SMS}$ + SD), QRS_{SMS} (SD + $START_{SMS}$). WH analyses comprise investigations of different wicket-gate closing laws during emergency load rejections (ELR), with normal behaviour and failures of PRVs.

4.2 Results

Case WMO-A presents emergency load-rejection of both turbines. Turbines steady-state discharge equals 2x20 m^3/s (rated discharge). Wicket-gate closing law is linear within 9 s. Results comprise the water level in the surge tank along with the maximum acceptance criteria, as well as tunnel discharge upstream of the surge tank and the discharge through the stand pipe (Fig. 3).

This case is used for calibration and verification of the developed software by comparison with the results of the transient analyses from the original design phase of the HPP [21] (Fig. 4).

Table 3. Overview of the analysed operational regimes of HPP Pirot

No.	Case	Initial Discharge [m³/s]		Final Discharge [m³/s]		Upper Reservoir Level [m]	Wicket-Gate manoeuvring law (WG_{ML})	PRV A - Active B – Blocked		Remark
		T1	T2	T1	T2			T1	T2	
Water-mass oscillation analyses										
1	WMO-A	20	20	0	0	615	9 s linear	A	A	SD
2	WMO-B	2.8	2.8	20	20	568	90 s linear	A	A	$START_{SMS}$
3	WMO-C	2.8 20	2.8 20	20 0	20 0	615	90 s linear 9 s linear	A	A	QSD_{SMS} (SD 240 s after $START_{SMS}$)
5	WMO-D	20 2.8	20 2.8	0 20	0 20	568	9 s linear 90 s linear	A	A	QRS_{SMS} ($START_{SMS}$ 270 s after SD)
Water hammer analyses										
6	WH-A	20	20	0	0	615	9 s linear	A	A	ELR
7	WH-B	20	20	0	0	615	Bi-linear, to 20% - 7 s to 0% - 10 s	A	A	ELR, WG bi-linear closing law
8	WH-A1	20	20	0	0	615	9 s linear	B	A	ELR with one PRV mulfunction
9	WH-B1	20	20	0	0	615	Bi-linear, to 20% - 7 s to 0% - 10 s	B	A	ELR, WG bi-linear closing law, one PRV mulfunction
10	WH-C	20	20	0	0	615	9 s linear	B	B	ELR, both PRVs mulfunction

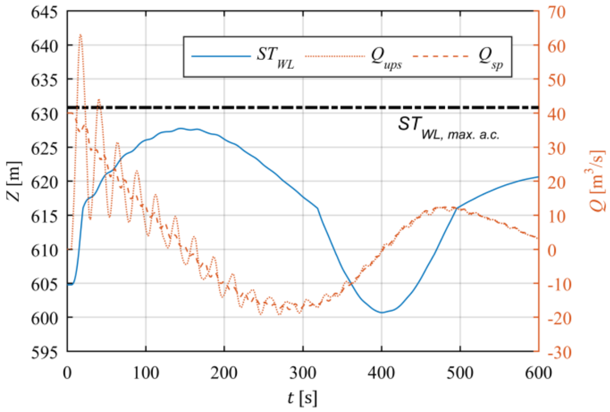

Figure 3. WMO-A - Water level in surge tank during shut-down (SD)

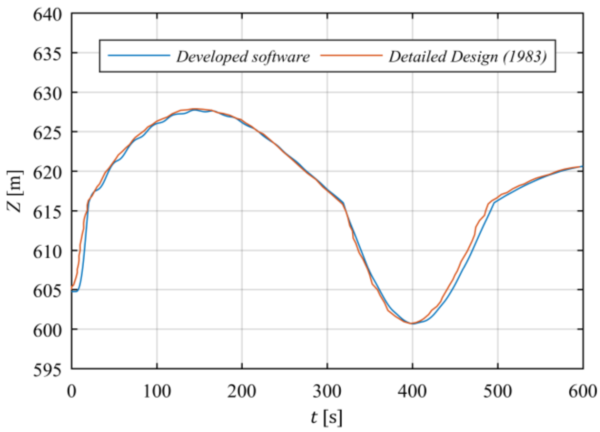

Figure 4. Results comparison beetwen the developed software and the Detailed Design (1983) for ST_{WL}

Case WMO-B presents simultaneous start of both turbines from speed-no-load (2x2.8 m³/s) to the rated discharge (2x20 m³/s). The upper reservoir level is at 568 masl which is the minimum operational water level of the reservoir. Wicket-gate openning law is linear within 90 s (Fig. 5).

Case WMO-C presents simultaneous start of both tur–bines from speed-no-load (2x2.8 m³/s) to rated discharge (2x20 m³/s), followed by shut-down at the most inconvenient moment (at approx. 240 s from the start). Wicket-gate closing law is linear within 9 s and openning is linear in 90 s (Fig. 6).

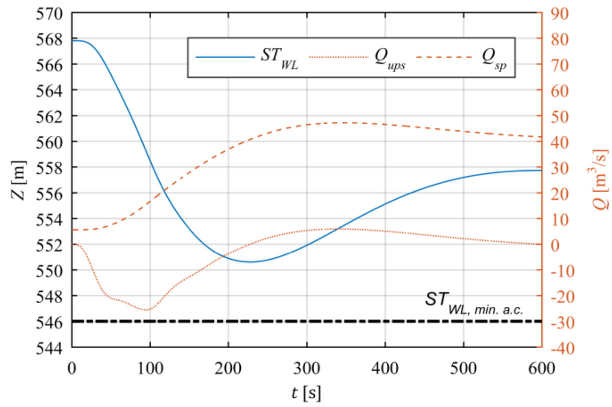

Figure 5. WMO-B - Water level in surge tank during simultaneous start-up of both turbines ($START_{SMS}$)

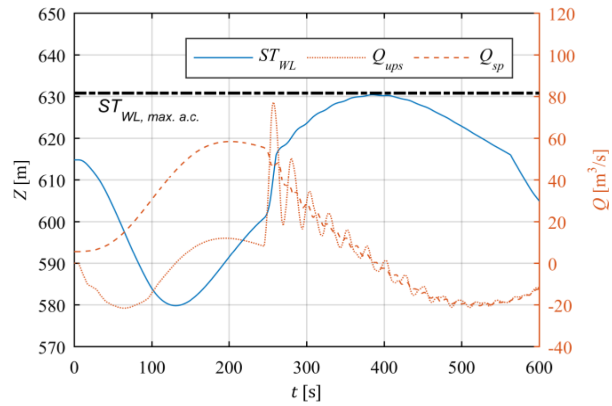

Figure 6. WMO-C - Water level in surge tank during shut-down of both turbines 240 s after simultaneous start (QSD_{SMS})

Case WMO-D presents shut-down of both turbines followed by simultaneous start after 270s. Wicket-gate closing is linear in 9 s and opening from speed-no-load (2x2.8 m^3/s) to rated discharge (2x20 m^3/s) is linear within 90 s (Fig. 7).

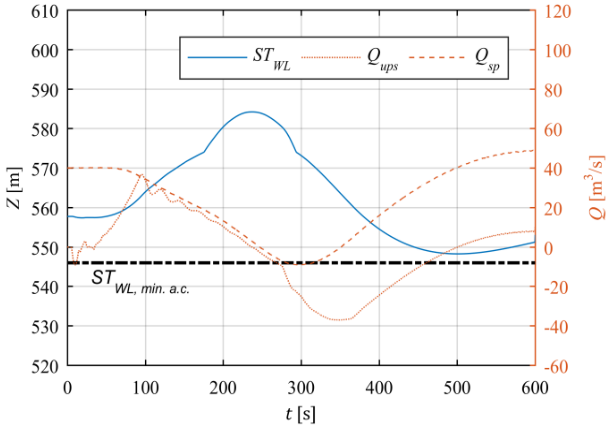

Figure 7. WMO-D - Water level in the surge tank during simultaneous start- up of both turbines 270 s after shut-down (QRS_{SMS})

In the case WH-A, emergency load-rejection of both turbines from rated discharge (2x20 m^3/s) is investi–gated. The closing law of a turbine wicket-gate is linear within 9 s. Both pressure relief valves are operating normally. Fig. 8 shows rising of turbine revolving speed and spiral casing head during the load-rejection and gradually slowing-down afterwards.

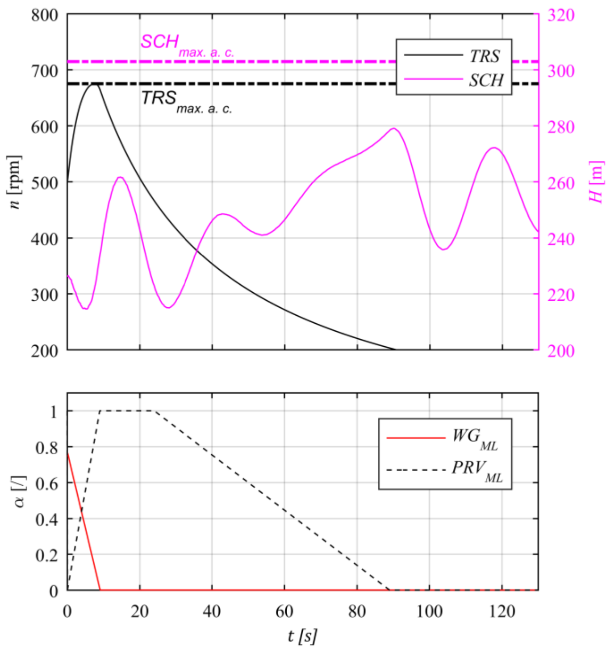

Figure 8. WH-A - Turbine revolving speed, head at the spiral casing and PRV manoeuvring law (PRV_{ML}) during linear WG closing (WG_{ML}) within 9 s

Head envelopes along the HPP waterways are retrieved at Fig. 9 for situation WH-A.

In the case WH-B, emergency load-rejection of both turbines from rated discharge (2x20 m^3/s) is inves–tigated. Wicket-gate closing is bi-linear from 100% to 20% within 7 s (11,4 %/s) and from 20% to 0% within 10 s (2 %/s). Fig. 10 shows time-history of turbine revolving speed and spiral casing head.

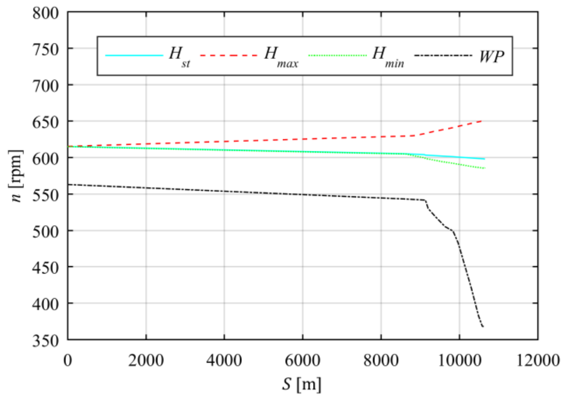

Figure 9. WH-A - Head envelopes during normal work of pressure relief valves and WG linear closing within 9 s

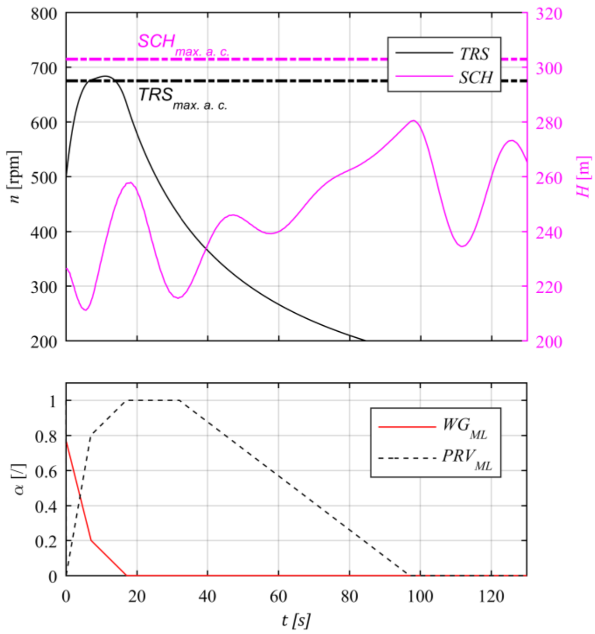

Figure 10. WH-B - Turbine revolving speed, head at the spiral casing and PRV manoeuvring law (PRV_{ML}) during bi-linear WG closing (WG_{ML})

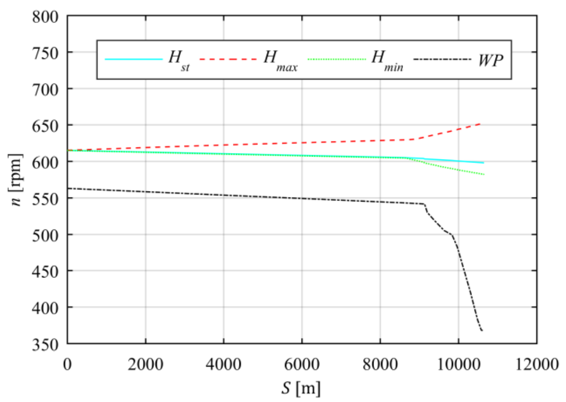

Figure 11. WH-B - Head envelopes for normal operation of PRVs and bi-linear WG closing

In Fig. 11 head envelopes are presented for the case WH-B.

In the case WH-A1, emergency load-rejection of both turbines from rated discharge (2x20 m^3/s) is inves–tigated. The closing of wicket-gate is linear within 9 s. One pressure relief valve is not functional. Fig. 12 shows time-history of turbine revolving speed and spiral casing head.

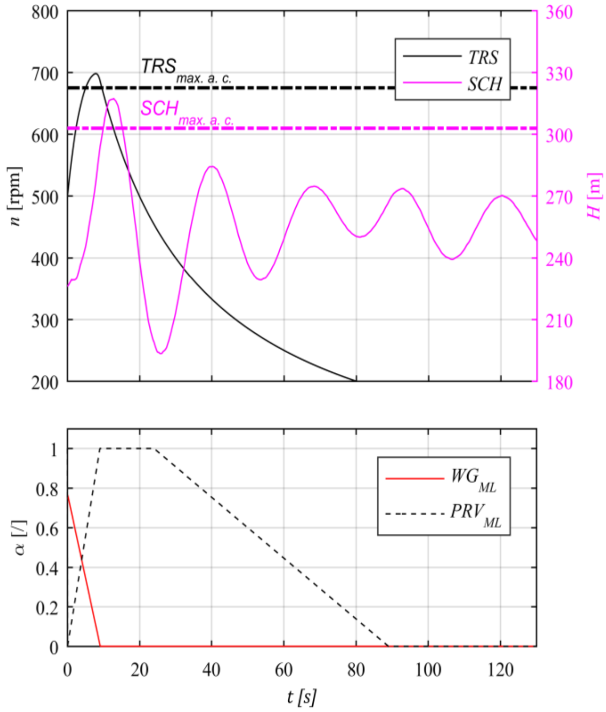

Figure 12. WH-A1 - Turbine revolving speed, head at the spiral casing and PRV manoeuvring law (PRV_{ML}) during linear WG closing (WG_{ML}) and one PRV failure

In Fig. 13 head envelopes are presented for the case WH-A1.

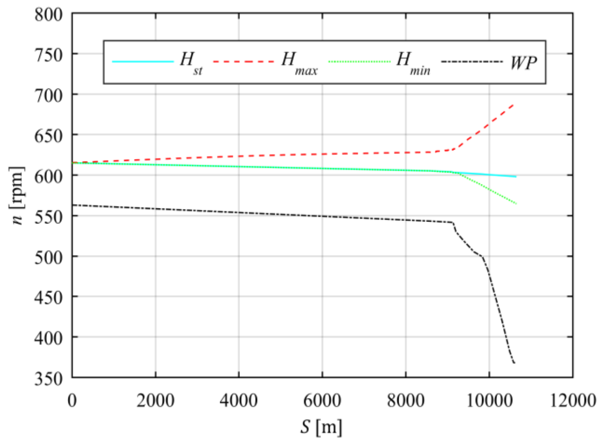

Figure 13. WH-A1 - Head envelopes for WG linear closing in 9 s, one PRV failure

In the case WH-B1, emergency load-rejection of both turbines from rated discharge (2x20 m^3/s) is investigated. Wicket-gate closing law is bi-linear from 100% to 20% within 7 s and from 20% to 0% within 10 s. One pressure relief valve is not functional. Fig. 14 shows time-history of turbine revolving speed and spiral casing head.

In Fig. 15 head envelopes are presented for the case WH-B1.

In the case WH-C, emergency load-rejection of both turbines from rated discharge (2x20 m^3/s) is investigated. Wicket-gate closing law is linear within 9 s. The upper reservoir is at 615 masl. Both PRVs are not functional. Fig. 16 shows time-history of turbine revolving speed and spiral casing head.

In Fig. 17 head envelopes are presented for the case WH-C.

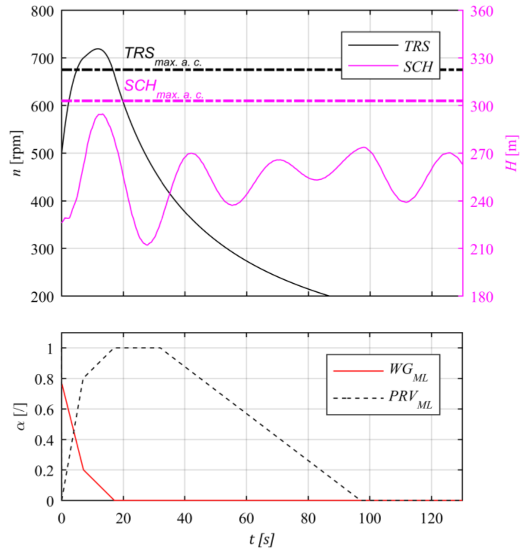

Figure 14. WH-B1 - Turbine revolving speed, head at the spiral casing and PRV manoeuvring law (PRV_{ML}) during bi-linear WG closing (WG_{ML}) and one PRV failure

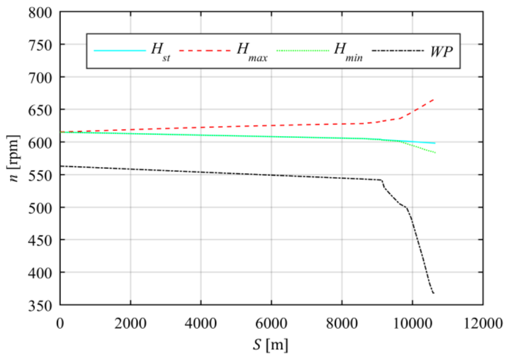

Figure 15. WH-B1 - Head envelopes bi-linear WG closing and one PRV failure

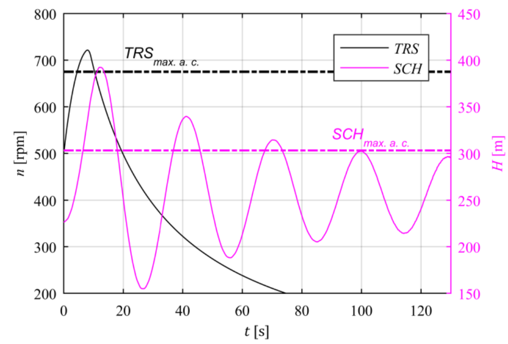

Figure 16. WH-C - Turbine revolving speed and spiral casing head for linear WG closing and both PRVs failure

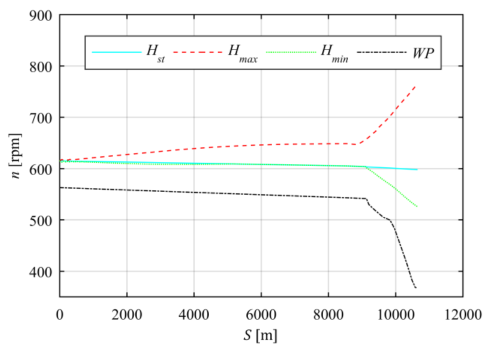

Figure 17. WH-C - Head envelopes for linear WG closing and both PRVs failure

5. DISCUSSION

Quick shut-down (WMO-C), in comparison to simple shut-down from a steady state of turbine rated discharges (WMO-A), represents the most extreme case that is used to investigate surge tank water elevation variation. The main reason for this phenomenon is the superposition that is established between oscillations in a system during start-up and oscillations during the succeeding shut-down. If the upper reservoir is at the maximum expected level, situation WMO-C would represent absolutely the most extreme case of the water level up-surge in the surge tank. This statement is confirmed by comparison of the results of these two cases – the maximum water level of the surge tank for the case WMO-A is 628.3 masl and for the case WMO-C is 630.4 masl (Fig. 18). This analysis is applied to check if the surge tank spills-over or not, meaning that it is used to determine maximum possible water level in the surge tank. Consequences of over-spilling may include flood of the surrounding cadastre parcels and harms to the surrounding area. The surge tank upper chamber crest-elevation is 631.30 masl and maximum water level that is calculated in this extreme regime is 630.4 masl (i.e. free-board being 0.9 m).

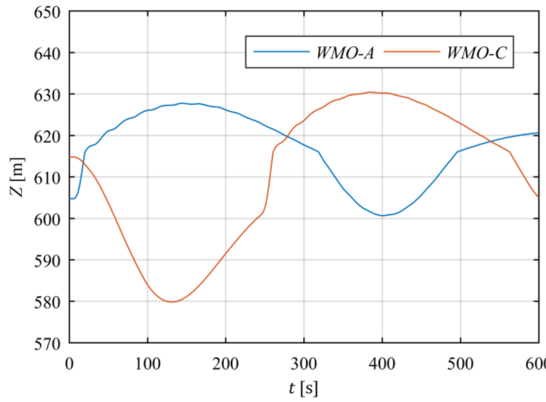

Figure 18. Surge tank water level - comparison of cases WMO-A and WMO-C

Start-up of the both turbines to the maximum load shortly after load-rejection (WMO-D) instead of start-up from steady state of speed-no-load (WMO-B) represents the most extreme case of the surge tank water elevation decrease. This investigation is applied to check the minimum possible level in the surge tank. This regime is investigated to avoid possible dewatering of the surge tank lower chamber (i.e. air intrusion into the waterways). It is of great importance to assure that the minimum water level remains safely above the lower chamber bottom. Minimum operational level in the surge tank for the case WMO-D is 547.3 masl and for the case WMO-B is 550.6 masl. Although the surge tank lower chamber bottom is at 540.62 masl, the form of the surge tank joint to the tunnel allows for minimum acceptance criterion of 546.0 masl (Fig. 19).

Air intrusion may cause unpredictable damages to the headrace waterways (blow-back water hammer in the derivation tunnel).

The case WH-A represents emergency regime of a HPP, with no unexpected malfunctions (normal operation of the PRVs). Head at the spiral casing is also investigated as an important parameter for the safety of turbine assemblies. These regimes are investigated over the time-frame of 130 because all the phenomena of importance in this analysis can duly be manifested in this time interval. One of the reasons for the research of the head envelopes is to calculate maximum pressures at various reaches of the waterways, so to allow for the shell-thickness dimensioning (newly designed HPPs) or check (refurbished HPPs). Malfunction of one or more of the safety elements (WH-A1, WH-B1, WH-C) is realistic during exploitation and should be duly considered.

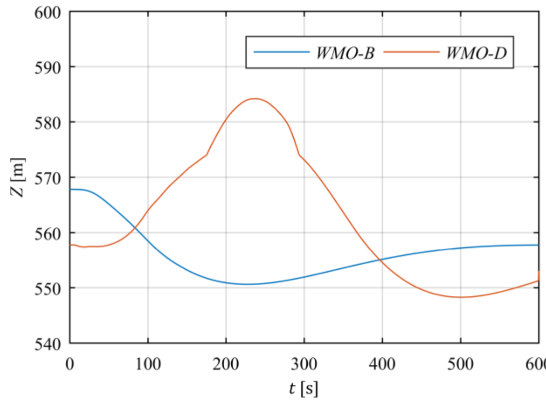

Figure 19. Surge tank water level - comparison of cases WMO-B and WMO-D

PRVs failure may not have a great effect on the turbine revolving speed as comparison of situations WH-A, WH-A1 and WH-C (Fig. 20), but analysis of spiral casing head as a main parameter shows extreme pressure oscillations (Fig. 21). In the case WH-C both PRVs malfunction is investigated although in the real calculations this regime is negligible with almost no probability to happen, but it surely represents absolutely the most extreme case of spiral casing head raise (pressure raise).

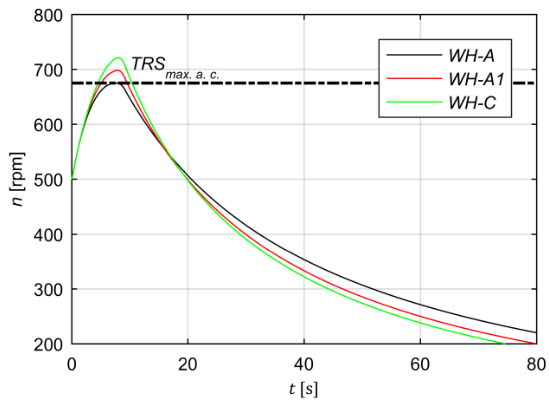

Figure 20. Turbine revolving speed- comparison of cases WH-A, WH-A1 and WH-C

The case WH-B (Fig. 10) shows that during the chosen bi-linear wicket-gate closing law, TRS is up to 683.5 rpm (36.6%) and acceptance criterion is 675 rpm (35%). Although this small difference may be negligible considering its practical meaning and software sensitivity, there is also an open space to further investigate the closing laws. SCH is far below its own acceptance criterion which means that faster closing law may be one of the solutions.

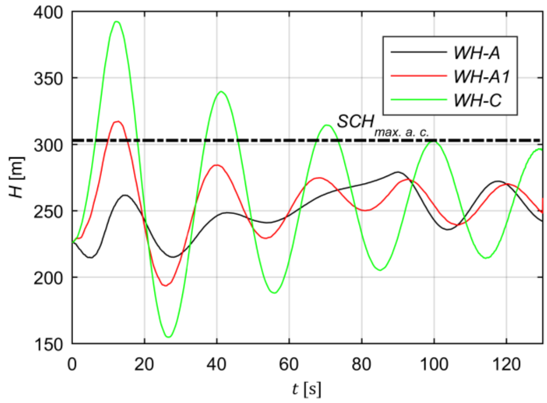

Figure 21. Spiral casing head- comparison of cases WH-A, WH-A1 and WH-C

6. CONCLUSIONS

Transients analyses present one of the most important and the most challenging issues during design of HPPs. It is important to keep transient heads and turbine revolving speed rise, as well as transient water elevations of the surge tanks (if any) within adopted limits (as per established acceptance criteria). Control of these phenomena is crucial for safe exploitation of an HPP. Aside of the safety issues, selection of the protective measures should also consider HPP functionality (exploitation costs) and economic (investment costs) issues. Numerical simulations were performed using original software. Further development of the software and verification should be based on experimental investigation at the HPP Pirot in-situ, as well as the other HPPs for which all the necessary input data can be acquired (reservoirs data, field topography, turbine hill chart, waterways characteristics etc.). Results show that pressure rise during load-rejection closely after start may be greater than the pressure rise during load-rejection from the corresponding steady state. Regarding WMO, superposing between oscillations during start-up and shut-down play significant role and it is important to analyse the most inconvenient moments to calculate maximum pressure in the derivation system, as well as extreme up-surge and down-surge of the surge tank. After satisfying results of calibration and verification, further research should be performed. Results retrieved during water hammer analysis should be justified through expe–riments done directly at the site of HPP Pirot, which would be the next step in the detailed analysis of transients for this HPP. The developed software is capable of expanding the field of research to the other hydraulic systems like pump stations, oil plants etc. Investigations by involving unsteady friction models should be employed in further research, as well.

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NOMENCLATURE

a.c.	acceptance criteria
CL	closing law
ELR	emergency load rejection
HOSC	hydraulic oscillations
HPP	hydropower plant
LGOV	level governing
ML	manoeuvring law
OPCH	open channel unsteady flow
PRV	pressure relief valve
QRS	quick re-start (QRS=SD+START)
QSD	quick shut-down (QSD=START+SD)
SCH	spiral casing head
SD	shut-down
SMS	simultaneous
SQS	sequential
START	start-up
STV	surge tank valve
ST_{WL}	surge tank water level
T	turbine
TGOV	turbine governing
TIV	turbine inlet valve
TRS	turbine revolving speed
WG	wicket gate (guide vanes apparatus)
WH	water hammer
WMO	water mass oscillations
WP	waterways (longitudinal) profile

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НУМЕРИЧКЕ АНАЛИЗЕ ХИДРАУЛИЧКОГ УДАРА И ОСЦИЛАЦИЈА ВОДЕНИХ МАСА У ХИДРОЕЛЕКТРАНИ ЗА ЕКСТРЕМНЕ РАДНЕ РЕЖИМЕ

Ј. Илић, А. Петковић, И. Божић

Анализе хидрауличних прелазних радних режима су неопходне у фази пројектовања нових и ревитализације постојећих хидроелектрана. У овом раду су разматрани прелазни процеси при специфичним екстремним радним режимима за деривациону хидроелектрану у којој су уграђени водостан и синхрони регулатор притиска на спиралном кућишту турбине. Посебни осврти су на анализама прелазних режима при осцилацијама водених маса и хидрауличком удару. Разматрани су разни експлоатациони режими и различити закони рада сихроних регулатора притиска. Резултати су добијени помоћу оригиналног софтвера развијеног за потребе ових анализа. Урађена је калибрација модела, а резултати су упоређени са анализама прелазних режима из фазе пројектовања постојеће хидроелектране.