Smart design requires updated design and analysis guidelines

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Abstract. This paper reviews several cases where there is an obvious and important margin between the ideal of smart design and the practical reality which often makes due with obsolete guidelines, outdated recommendations and leads to expensive maintenance troubles. Stated alternatively, this paper is a plea for an attempt to better integrate high technology, experience, knowledge and economics so that both owner and human interests can be better supported and protected. To this end, several well-known plants (Sayano-Shushenskaya, Grand Coulee, Niagara Falls, Richard B Russell, Iron Gates 2, Jenpeg, Bajina Basta, Zvornik, to name a few) have been briefly analysed to clarify the crucial need for updated approaches. Of course, whether the plant is large or small, designing, constructing, operating and updating hydropower plants is a complex set of tasks. Any hydroelectric installation, as a rule, should be designed in several stages. At each stage, entire project documentation should be reviewed by independent reviewers. Reducing the number of analyses, or limiting their scope, with no clear justification except for an attempt to save a little on cost upfront, or worse yet, neglecting the design procedures, can put a project at risk. For a variety of reasons the continuity of knowledge and experience has been lost nearly everywhere. The paper argues that an organized and multidisciplinary transfer of experience is a priority task to be undertaken by the electricity sector. There is a clear need to plan, finance and implement various long-term initiatives; it is urgent that decisions to address this be made now to preserve the currently available knowledge and the almost 200-years of project experience.

1. Introduction

1.1. Business and high-tech technology

Businesses, investments and financial decisions frequently are not supported by high developed technology and verified science. Main and understandable reason reduce investments. None experienced designers and even not following all design levels (feasibility study, general design detailed design, and reconstruction, particularly enlargement and/or increase of power) increase risks of failure and inefficiency.

1.2. Guidelines, recommendations, and standards

To support business and investment guidelines, recommendations, and standards should (must) be updated and clearly point out what should and what must be done to make a safe and environment friendly project and plant.
1.3. Hydro projects
The design, construction and operation of a hydropower plant involve many challenges in environmental and hydrologic assessments, engineering planning and design, financing with far-sighted political perspective, demanding construction and supervision, painstaking commissioning and troubleshooting, and meticulous operation and control. All details must be well conceived, accurately executed, and carefully coordinated for a project to achieve economic, social, technical and environmental success. Overseeing or improperly integrating such details can cause great complications. One such vital detail is hydraulic design of tailrace tunnels, for which the paper overviews a few particular hydro systems and provides background on the observed water column separation and rejoinder phenomena. It has been a bias favoring the analysis of upstream hydraulic components including the turbine, while less attention has been paid to the downstream water passage, often treating the design of draft tube and tailrace as mere second thought. Yet, many important, and potentially destructive, hydraulic phenomena occur in the draft tube, its extension, and/or the pressurized tailrace tunnel, especially if the tailrace is long.

1.4. Draft tube water column separation
In order to avoid the danger of water column separation and consequent reverse waterhammer, the minimum pressure in any conduit (tunnel, penstock, pipeline), as a design criterion, should not fall below 50 kPa (0.5 bar), even temporarily [4][5][26][27][36][37]. This minimum pressure must be the instantaneous value during a transient event and at the highest position of waterway, typically at the runner outlet or at the upper limit of draft tube lining. Since on site pressure transducers only can be attached to the wall of draft tube, and since the water in the draft tube is usually in rotary motion, the measured pressure is actually the maximum value for a given cross-section; the pressure in the vortex core, by contrast, is likely at absolute vapor pressure or at the air release pressure of the dissolved air, or slightly above this if air injected [15][23][45]. Therefore, the measured pressures cannot be used directly as a design criterion. Some manufacturers have empirical pressure and velocity distribution data for their machines [21], and others have measured data from model turbine draft tubes [15]. All the data for each machine must be carefully evaluated because the similarity laws do not apply to two-phase flows [16][33][34].

1.5. Analyses of draft tube water column separation
In practice, the lowest transient pressures are typically approximated using one-dimensional waterhammer theory and transient modeling, which only represents the “cross-sectional average” pressures which are usually higher than those found in the vortex core and lower than those measured at the wall of draft tube cone. In addition, the numerical analysis results could be uncertain and inaccurate around the unstable zones of turbine characteristics, so the numerical analysis must be thoroughly performed and experimentally confirmed. For more information read article [40] published in this proceeding. A larger safety margin is prudent for the minimum pressures in the draft tube, particularly given the complexity and uncertainty of these transient flows, as well the lack of an applicable similarity law. Moreover, the speed increment of the runner, in runaway condition, is crucial since the voids formed by the centrifugal force of the high-speed rotating water can be large; the pressure rise caused by even slow accelerations/decelerations of the tailrace water may have a strong influence on void collapse.

1.6. Vortex core and water column separation
For a hydro project it is particular important to understand the phenomenon of water column separation and subsequent column rejoinder arising from the reverse water hammer in the draft tube [1][6][14][16][26][27][29][43][44][45][46][47][51][52] therefore a repeatedly presented here. Water column separation could occur during either steady or transient conditions when low pressure establishes voids in the water column. Specifically, this phenomenon occurs when the local pressure drops below the vapour pressure of water or the partial pressure of dissolved gases (usually air). The
dramatic pressure rise that typically accompanies the collapse of such voids (water column rejoinder) can be sufficient to crack the internal linings of conduits and damage both the turbine and other hydraulic components. Perhaps more insidiously, this damage can progress unnoticed, frequently observed only after repeated transient events, thus, creating a ‘time bomb’ of future hydraulic and structural problems. However, the phenomenon of draft tube surge has not been fully discussed in English although a few articles are listed in the References. A predominant condition associated with reverse waterhammer is that the runner is effectively dewatered when the flow reverses from the draft tube. Only if the axial component of flow velocity is lower than the allowable value (around 0.5 m/s) will the impact force on the runner blades from the reversing water be small and unlikely to cause damage [38]. In addition, runner lifting should also be checked during reverse waterhammer, that is, the axial hydraulic force during the entire transient must be smaller than the weight of the rotating parts. In horizontal machines thrust bearing controls this force.

In order to prevent severe rejoinder of partially separated columns of water, the large vortex void in draft tube should be avoided. As aforementioned, the pressure distribution in the draft tube cone is inherently uneven (due to the helical motion of the flow), with the maximum pressure occurring at the wall and the minimum near the center (Figure 1). To be more precise, the minimum pressure occurs near the center of the vortex core, a complex rotating tube of water, vapor and air, which usual forms in the draft tube. The vortex core is unstable as a result of the swirl (tangential component of absolute velocity of water outflowing from the turbine runner) induced by the action of the turbine blades [23]. It is important to recall that transducers mounted on the draft tube wall invariably record the greatest cross-sectional pressures, instead of the lowest pressures in the vortex core at the center of draft tube. In other words, even when the measured pressure is significantly high, the core pressure could be at vapor pressure (or air release pressure), or perhaps slightly above the vapor pressure if air has been injected into the system. Clearly, then, it is inappropriate to rely on the pressures measured on the draft tube cone to judge whether the minimum pressure exceeds 0.05 MPa. Computational fluid mechanics (CFD) and numerical approaches clearly hold out some promise but they are unfortunately far from being sound solutions to the challenge of measuring and predicting the possible range of draft tube pressures and velocities due to the limited accuracy and numerical stability. The difficulty arises from many sources, including the multi-phase, unsteady, asymmetrical, three-dimensional and oscillatory nature of the flow, and the complex interactions between the flow and the machine unit (see photos in Figure 1 and Figure 2).
Overall, the inherent complexity and significance of these events demand an empirical approach to predict the occurrence of water column separation in draft tubes. It is essential that all pressure data be carefully evaluated. This is particularly true since, we emphasize, no similarity law is applicable to transient and/or two-phase flows [16] while the equations based on similarity still apply to the boundary conditions of the pump-turbine. In practice, the lowest transient pressure in the turbine system is typically calculated based on one-dimensional waterhammer theory and thus represents the “cross-sectional average” value which is lower than the measured one but higher than that in the vortex core, Figure 1.

Any mathematical solution in the zone of instability is highly inaccurate and uncertain; fluctuations in the multiphase unsteady vortex core further complicate the flow conditions, where model test data cannot be accurately transferred to the prototype.

2. An approximate analysis of long tailrace tunnel

The length of tailrace tunnel as a function of closing time of guide vanes and flow speed in the tunnel in order to avoid the water column separation can be calculated applying the approximate equation

\[ L = \frac{k g T_s}{2v_0} \left( 8 - \frac{v_0^2}{2g} - h_s \right) \]

where: \( L \) = permitted length of tailrace tunnel, \( T_s \) = closing time of guide vanes, \( k = 0.6 \) to \( 0.7 \) empirical coefficient, \( v_{0t} \) = water speed at the runner outlet - the draft tube cone inlet, \( h_s \) = suction head \( v_0 \) = flow velocity in the tailrace tunnel. This approximate equation is based on the rigid water theory neglecting the elasticity [15] and as we know, is not published in English.

In general design, detailed design, and reconstruction, particularly enlargement and/or increase of power, modern computer method should be applied and result verified on site in commission and trial operations.

3. Published history of reverse waterhammer

Some published and known history of water column separation and rejoinder resulting in troubles accidents and catastrophes are listed with brief descriptions when available. Much more unpublished and unknown cases occurred. All of them and lessons learned should be published to protect lives, environment, investors and owners.

3.1. Sayano-Shushenskaya Catastrophe 2009

The official report, released on Oct. 3, 2009, blamed poor management and technical flaws for the accident. According to the report, repairs on Turbine 2 were conducted from January to March 2009, and a new automatic control system--meant to slow or speed up the turbine to match output to fluctuations in power demand--was installed. [1] It seems that this adjustment has been done without Adjustment or Modification in Project Design or parameters have not been applied in commissioning and trial operation resulting in catastrophic accidents and 76 deaths, 9 of 10 turbines were damaged or destroyed, and 6,400 MW supply, was lost. Ref. [1][28] concluded that reverse waterhammer (water column separation) was the source of hydraulic force which as an explosion had ruined the turbines and generators. From Fluid Mechanics and Hydraulics point of view only reverse water hammer could have been a source of such force.
Again, Enlargement, Redesign, Adjustment or Modification in Project Design or as a special one titled Hydraulic Transient Analyses should have analysed to prevent catastrophic! The implications are profound: it is too expensive to make our own mistakes; we must learn efficiently from others: we must read; we must learn; we must teach. Updated, standards, guidelines, and recommendations should (must) be applied.

Figure 3 shows some information for this accident described in References [1][13].

![Figure 3 View of the plant, the plant after catastrophe, illustration of reverses waterhammer](image)

3.2. **Stugun Power Station, 1992**
An accident occurred in 1992 on commissioning testing at Stugun hydro power plant located in the north of Sweden. Tests were made due to renovation of the generator and the turbine. Reverse waterhammer has broken a runner blade and head cover. [14] A Reconstruction, Redesign, Adjustment or Enlargement Design should have been reviewed.

3.3. **Akkats power station, 2002**
In 2002, an incident occurred on commissioning testing at Akkats rebuild plant located in Sweden. Although extensive repairs were made, it only proved to regain 80% of generation capacity. During a load rejection the guide vanes were closed rapidly. A water column separation collapsed and caused a lifting of the runner with 700 tons of shaft and generator rotor. [14][3]. A Reconstruction, Redesign, Adjustment or Enlargement Design should have been again carefully accomplished.

3.4. **Kaplan turbine broken down in Sweden, 1986**
Kaplan turbine has been broken down in Sweden in 1986. The turbine over speed signal was reached and emergency stop level closed the guide vanes. The emergency closure at overspeed, a more severe initial condition, has been enough to result in an accident [14].

3.5. **Ozbalt plant. 1976**
Kaplan turbine accidents, at Ozbalt plants, former Yugoslavia 1976; unpublished. The accident similar to the Zvornik power plant which occurred a year before. See Below.

3.6. **Zvornik power plant, 1975**
Kaplan turbine accidents, at Zvornik plants, former Yugoslavia 1975. [44][45] [49].

3.7. **Study on the reverse waterhammer**
Incidents due to turbine quick closures have occurred in two Kaplan turbines in former Yugoslavia (Ozbalt and Zvornik); Zvornik plant broken blade shown in Figure 4. The Faculty of Mechanical Engineering, University of Belgrade, and Association of Power Industry, Belgrade, then jointly undertook a study on the reverse waterhammer in hydraulic turbines (managed by Pejovic), the key results are summarized in a series of articles [10][12][29][26][38][44][45]. The investigators also described and published the accident that had occurred at Zvornik power plant.

3.8. **Russia published accident, 1965**
Kaplan turbine accident in Russia; published [51][56]. Broken blade shown in Figure 5.
3.9. Ice Harbor Plant, 1965
Ice Harbor Plant, the US, Kaplan turbine No. 2 accident, 1962; unpublished, report [50].

3.10. Ovcar Banja plant butterfly valve accident, 1971
Quick sudden closure of butterfly valve, at intake structure, the turbine spiral case exploded, small 4 MW plant, former Yugoslavia 1971; unpublished; report [25].

4. History of other cases
Issues of other cases could not be presented here as the length of articles is limited. Some challenges and descriptions are listed in these articles [5][10][11][12][17][26][32][34] [39] [40][41][47] etc.

Cases of well-known plants such as Grand Coulee, Niagara Falls Plants, Iron Gate, Janpeg, sometimes have no better choice or saved upfront money or in the worst case designed by inexperienced experts or neglected design procedures (feasibility study, general design detailed design, and reconstruction, particularly enlargement and/or increase of power) as well as reviews and revisions by independent reviewers. Grand Coulee has no better choice but to build (Figure 6) in the side bank forming unfavourable “S” form inflow into the intake structure, Figure 6; Sir Adam Back 2 Formed “S” inflow to save money upfront. Many inexperienced designers copy this layout in spite that in these cases efficiency is reduced and maintenance cost increased.

Application of obsolete standards, guidelines, recommendations and textbooks could have also been reasons.
5. Catastrophe prevented in trial operation
As a member of Canadian International Consortium: Hydro Québec & Rousseau Sauvé Warren in Iranian Company At the first phase of 2000 MW (8x254 MW) "Masjed-E-Soleyman" Hydroelectric Plant turbine Farab S Pejovic reviewed documentation of equipment to be delivered on site. Only waterhammer analysis was done at the very beginning and in the conclusion pointed out that calculation should be repeated at next design level. manufacturer submitted incomplete transient calculations. Water column separation was not analysed in the long tailrace tunnel shown in Figure 7, left. At the construction stage it was decided to omit downstream surge tank; this was done without any transient analyses.

The reports [30][31] submitted in 1998 were discussed and reviewed and many letters submitted. Unfortunately these reports and letters were ignored.

In trial operation water column separation verified with high pressure peaks measured at their rejoinder with the runner blades as presented in Figure 7, right. The panel of experts nominated to solve the problem verified during commissioning and trial operation also has not protected adequately the system and controversial articles were published [7][30][31][41][42][43][44][48].

A better organized design, reviews and involvement of experienced expert could have made the project at lower risk and costs.

Figure 7  The second phase of 4000 MW (8x250MW) hydroelectric plant under construction; the first phase in operation partially protected by air injection into the draft tube. Diagram: Two units 75% load rejection with air admission (the red line, June 2004) comparing with one unit 100% load rejection without air injection (the blue line, Nov. 2003)

6. Standards, guidelines, books
Many important experiences and knowledge accumulated in last century are not yet introduced into the publications and standards, guidelines and recommendations such as IEC, ASMA, ASCE, IEEE, EPRI, IEA, USBR, etc. The young experts therefore have nowhere to read and learn about phenomena very important for the safety of electric plants. In addition a course the Design of Hydro and Wind Electric Plants is thought at the University of Toronto for the first time offered to students in Winter 2009; so far this is the first time that the Design of Hydroelectric Plants was presented to the students in North America.

7. Conclusions
Those who design and construct complex hydraulic systems have to face many challenges. Even routine issues such as the trade-off between capital and operating costs invariably involve an assessment of events that might happen in the future, a realm of great uncertainty. Although this paper discusses specific cases, the goal is not to cast blame, assign fault, or imply that the related decision-making is easy. In almost all such cases, only hindsight is sharp and clear. However, these issues have arisen before, and will continue to arise, until the associated challenges are brought more consciously into the open where they can be discussed and debated.

Since water hammer calculations are usually based on one-dimensional models, the results represent average values of pressure heads and, thus, the variation of pressure over the draft tube cross-section must be carefully considered. Moreover, the speed increment of the runner, particularly
in runaway condition, is crucial since the voids formed by the centrifugal force of the high speed rotating water can be large; the pressure rise caused by even slow accelerations/decelerations of the tailrace water could have a strong influence on void collapse. Therefore, transient analysis must be thoroughly performed and confirmed experimentally. A larger safety margin is prudent for the draft tube coefficient, particularly given the complex and difficult-to-model nature of these transient flows.

Air admission is a way of controlling water column separation. Field tests show that the injection of compressed air reduces the severity of transients during load rejection, even for insufficiently submerged turbines. Thus, air injection is useful in underground power plants where the potential to increase the power output is constrained by the excessive negative surges in draft tubes. However, being a reactive and real-time safety concept, it relies on the controller’s dexterity and skill, and it must be carefully designed, tested, and maintained.

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9. References
[1] Sayano–Shushenskaya power station accident, (2009), Wikipedia, http://en.wikipedia.org/wiki/2009_Sayano%E2%80%93Shushenskaya_power_station_accident
[2] A power station accident, halffast, (2012), http://www.slideshare.net/halffast/accident-at-russias-biggest-hydroelectric-plant-11695486
[3] Akkats Power Station, Vattenfall's European energy company, http://powerplants.vattenfall.com/node/338
[4] ASME HPTC (Pejovic S., co-author), (1996), The Guide to Hydropower Mechanical Design, HCI Publication.
[5] ASME HPTC (Bryan K., Pejovic S., co-authors), (2011), The Guide to Hydropower Mechanical Design, new edition under review.
[6] Borciani S., Thalman R., Influence of on Average and Instantaneous Characteristics of Turbines and Pump-Turbines (in Franch), La Hoille Blabnche, 1982, No. 2/3.
[7] Brekke H., Jacob, Th. Kiani A.S., Leyland B., Pejovic S. (2004), Transient Problems upon Load Rejection Masjed-e Soleymen Case Study, Portugal, Hydro 2004, paper 4.01
[8] Brekke H., Jacob Th., Leyland B., Pejovic S. (2003) “Transient Problems upon Load Rejection”, Masjed-e-Soleymen Panel of experts report.
[9] Design Criteria of the Tailrace Tunnel to Prevent Water Column Separation, Toshiba, report, 1976.
[10] Gajic A., (1983), A Contribution to the Investigation of Unsteady-State Phenomena in Hydro Power Plants (In Serbo-Croatian), part of Ph.D. thesis, University of Belgrade, Yugoslavia, Vol.1.
[11] Gajic A., (1993), Kaplan Turbine Incidents Due to Reverse Water Hammer and Mathematical Model Confirmed by the Field Tests, (Invited paper), Proceedings of the International Symposium on Aerospace and Fluid Science, Institute of Fluid Science, Tohoku University.
[12] Gajic A., Pejovic S., Ivljianin B., (2003), Reverse Waterhammer - Case Studies, Proceedings of the International Conference on CSHS03, Belgrade.
[13] Hasler J.P., (2010), Investigating Russia's Biggest Dam Explosion: What Went Wrong, http://www.popularmechanics.com/technology/engineering/gonzo/4344681
[14] Hillgren N., (2011), Analysis of hydraulic pressure transients in the waterways of hydropower stations, Teknisk- naturvetenskaplig fakultet, UTH-enheten. UPTEC ES11007 Examensarbete 30 hp, http://uu.diva-portal.org/smash/get/diva2:412851/FULLTEXT01
[15] Krivtchenko G. I., Arshenevsky N. N., Kvyatkovskaya E. V., Klabukov V. M. (1975),
Hydraulic Transients in Hydroelectric Power Plants, (in Russian), Moskva.

[16] Lee T. S., Pejovic S., (1996), Air Influence on Similarity of Hydraulic Transients and Vibrations. Transaction of the ASME, Journal of Fluids Engineering, Vol. 118.

[17] Maricic T., Karney W. B., Pejovic S., (2009), Knowledge Transfer with Intention to Improve Design While Reducing Operational Expenses, VIPSI-2009, Belgrade.

[18] Marston D.L., (1996), Law for Professional Engineers, McGraw-Hill-Ryerson.

[19] Martin C. S., Post Accident Report, Frequency, Resonance, and Hydraulic Transient Analysis, Bhira Pumped Storage Installation, the Tata Power Company Limited, 1995.11

[20] Martin C. S., (1986), Stability of Pump/Turbine During Transient Operation, Fifth BHRA International Conference, on Pressure Surges, Hanover, West Germany.

[21] Murray H., (1980), Hydraulic Topics in Development of High Head Pump-Turbine and Investigation on Related Problems in Japan, General Lecture, 9th IAHR Symposium on Hydraulic Machinery and Cavitation, Tokyo, Japan, pp. 1 - 14.

[22] Nicolet C., Alligné S., Kawkabani B., Kouintik J., Simon J.J., Avellan F., (2009), Stability Study of Francis Pump-Turbine at Runaway, 3rd IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, October 14 – 16, Brno, Czech Republic. Link: [http://www.powervision-eng.ch/Profile/Publications/pdf/IAHR_WG1_2009_1.pdf](http://www.powervision-eng.ch/Profile/Publications/pdf/IAHR_WG1_2009_1.pdf)

[23] Obradovic D., Pejovic S., Arnautovic D., Gajic A., Cavor R., (1986), Guide for Numerical and Experimental Tests of Transients in Hydraulic Installations, (in Serbian), Electricy Board of Serbia, Belgrade, pp 1- 64.

[24] Ohashi, H., (1991), Editor, Vibration and Oscillation of Hydraulic Machinery, Avebury Technical.

[25] Ovcar Banja hydro electric plant accident, (1971), report, Serbia (former Yugoslavia).

[26] Pejovic S., Chapter 12 Hydraulic Transients, ASME Guide to Hydropower Mechanical Design, Prepared by ASME HPTC, 2011, new edition under review.

[27] Pejovic S., (1996), Chapter 12 Hydraulic Transients, The Guide to Hydropower Mechanical Design, Prepared by ASME HPTC, HCI Publication, pp. 374.

[28] Pejovic S., Electricity and Water Systems at High Risk - Hydro Projects: Lessons to Learn! [http://myelab.net/cane/HydroProjectsOttawa.pdf](http://myelab.net/cane/HydroProjectsOttawa.pdf)

[29] Pejovic S., (1977), Hydraulic Transients and Reverse Waterhammer (in Serbo-Croatian). Institut Masinskog fakulteta, Beograd.

[30] Pejovic S., Mesjad-E-Soleyman (1998), Analysis of Draft Tube Flap Gate, Hydro Québec International, RSW International, Teheran, report.

[31] Pejovic S., (1989), Pressure Surges and Vibrations in Hydropower Plants - Experiences in Yugoslavia, The Current State of Technology in Hydraulic Machinery, International Editorial Committee Book Series on Hydraulic Machinery, Gower Technical, , pp. 177-204.

[32] Pejovic S., (1989), Similarity in Hydraulic Vibrations of Power Plants, Joint ASCE/ASME Mechanics, Fluids Engineering, and Biomechanics Conference, San Diego, USA, American Society of Mechanical Engineers, Paper 89-FE-4, pp. 5.

[33] Pejovic S., (2002), Troubleshooting of turbine vortex core resonance and air introduction into the draft tube, IAHR Symposium, Lausanne, Switzerland.

[34] Pejovic S., (2000), Understanding the Effects of Draft Tube Vortex Core Resonance, Hydro Review Worldwide, HCI Publications, p. 28-33.

[35] Pejovic S., Boldy A.P.,(1992), Guidelines to Hydraulic Transient Analysis of Pumping Systems, P & B Press, Belgrade – Coventry.

[36] Pejovic S., Boldy A.P., Obradovic D., (1987), Guidelines to Hydraulic Transient Analysis, Technical Press, England.
[38] Pejovic S., Gajic A., Obradovic D., (1980), Reverse Water Hammer in Kaplan Turbines, X IAHR Symposium, Tokyo, pp. 489-499.
[39] Pejovic S., Gajic A., (1989), Cases and Incidents Due to Hydraulic Transients - Yugoslav Experiences, International Congress on Cases and Accidents in Fluid Systems, São Paulo, Brazil, pp. 181-223.
[40] Pejovic S., Karney B., (2014), Guidelines for transients are in need of revision, published in this proceedings.
[41] Pejovic S., Karney B.W., Zhang Q., Kumar G., (2007), Smaller Hydro Higher Risk, IEEE Trans CD.
[42] Pejovic S. Karney W.B. and Zhang Q. (2004), Masjed-E-Soleyman Hydraulic Transients. Water Column Separation in the Draft Tube, Draft Tube Surges, Panel of Experts Mission of November 2003, Report.
[43] Pejovic S., Karney B., Zhang Q., (2004), Water Column Separation in Long Tailrace Tunnel, HYDROTURBO, Brno.
[44] Pejovic S., Kršmanović Lj., Gajic A., (1978), Reverse Waterhammer and Accident in Hydro Power Plant “Zvornik” (in Serbo-Croatian), Masinski Fakultet, Belgrade, pp. 90.
[45] Pejovic S., Kršmanović Lj., Gajic A., Obradovic D., (1980), Kaplan Turbine Incidents and Reverse Waterhammer, Water Power and Dam Construction, August 1980., pp. 36-40.
[46] Pejovic S., Kršmanović Lj., Jemcov R., Crnkovic P., (1976), Unstable Operation of High-Head Reversible Pump-Turbines, IAHR 8th Symposium, Leningrad.
[47] Pejovic S., Obradovic D., Gajic A., (1984), Hydraulic Transients in a Power Plant - Mathematical Modeling Confirmed by Field Tests, Hydrosyft 84, Portoroz, pp. 5.57-5.67.
[48] Pejovic S., Samadzadeh B., Supervised by Khris R., (1998), Masjed e Soleyman Stability Analysis, Report, Hydro Québec International, RSW International, Teheran, Report.
[49] Pejovic S., Zhang Q., Karney B., Gajic A., (2011), Analysis of Pump-Turbine “S” Instability and Reverse Waterhammer Incidents in Hydropower Systems, Key invited presentation, 4-th International Meeting on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, Belgrade, October 26-28, 2011, http://www.stanpejovic.com/IAHR WG Bgd Oct 2011 Pejovic BG KZ AG Keynote Instability Reverse WH Incidents.pdf
[50] Report on investigation of accident to Turbine No.2 in PIT No.1 during sudden load rejection tests at Ice Harbor Lock and Dam, (1962), Corps of Engineers, Walla Walla District, Contract DA-45-154-CIVENG-56-166 / S.O. 78930, February 2, 1962.
[51] Time V.A., (1960), Reverse Water Hammer in the Kaplan Turbine Drat Tube (in Russian). Electrichestie Stancii, No 3.
[52] Wylie E.B., Streeter V.L., (1993), Fluid Transients, McGraw-Hill.
[53] Chaudhry M. Hanif, (1987), Applied Hydraulic Transients, Van Nostrand Reinhold Company.
[54] Suter P., (1966), Representation of Pump characteristics for calculation of Water Hammer Sulzer Technical Review, Research Number, 1966, (11):9-100.
[55] Thorley, A.R.D. and Chaudry, A., (1966), Oumo Characteristics for Transient Flow Analysis. Proc., 7th Int. Conf. On Pressure Surges and Fluid Transients in Pipelines and Open Channels, Harrogate, UK, 16-18 April, 461-475.
[56] Zmuđ A.E., Litkovskii J.A., Rubek N.N., (1960), Reverse Waterhammer in Hydroelectric Plants (in Russian). Gidroelektromashinostroenije, No 2.