

Guidelines for transients are in need of revision

S Pejovic¹, B Karney²

¹Prof. Emeritus, 300 Webb Drive, Mississauga, Ontario, Canada L5B 3W3

²Civil Engineering Department, University of Toronto, Canada, M5S 1A4

The corresponding author's e-mail address: stan.pejovic@utoronto

Abstract. Although considerable knowledge has been built-up over the years, the design of various hydroelectric plants, particularly pumped-storage plants, has not always made full use of this knowledge. Mathematical instabilities, which could be resolved by experienced experts, and real physical unavoidable instabilities, make software application by experts not educated and experienced in subject extremely dangerous: bad things can happen if one can't distinguish inaccurate unrealistic results from reasonable good ones. Additionally, in a number of cases there is considerable evidence that already published guidelines, recommendations and standards have not been consistently applied. As a consequence, vital parameters relating to overall safety and sustainable operation which could have been based on the experience and knowledge of designers and equipment suppliers have been neglected. For instance, contrary to certain common working assumptions, the minimum pressure in a draft tube cannot be any constant pressure to fit the complex flow conditions at the exit of the runner. When such realities are combined with pump-turbine "S" instability there is a further increase in the risk of damages and accidents. Rather, a more realistic set of procedures must be applied. What makes such considerations particularly vital is that pumped-storage plants have such excellent potential for further exploitation as they represent a potentially significant environmentally clean load that may help compensate for power variations in the grid and the need to limit wind power output. Energy storage – if well designed and operated – has a great potential for making the overall system and market more efficient and reliable. It is not an exaggeration to say that pumped storage systems could substitute for up to 50% of nuclear and coal generating plants. They are easily manageable and impressively can be 75 - 85% efficient across the energy storage cycle. This work maintains that some crucial technical areas have lost the benefit of valuable experience and knowledge that has accrued in more than 100 years. The poorly coordinated transfer of practical and theoretical experience appears to be the root cause of this loss. The consequences are an unstable market and investment climate, and a greater frequency of accidents, higher inefficiency and the need for more common troubleshooting; yet many of the same problems which have appeared in recent years can be expected to continue to occur with distressing regularity if appropriate steps are not taken. The required and organized multidisciplinary transfer of experience is a major and challenging task, but one that needs to be undertaken by nonpartisan organisations. It is imperative that decisions to achieve this goal be made now. There is a clear and pressing need to plan, finance and implement a variety of long-term initiatives.

1. Introduction

Hydraulic transients are pressure changes caused by pressure waves propagating throughout the hydraulic system. High pressures and stresses can build up when the frequencies of these pressure



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waves are close to the natural frequencies of water conduits and/or mechanical and electrical systems, but in unstable systems consequences are unpredictable and unrepeatable; mathematical programs run into instability delivering uncertain unrealistic results.

1.1. Guidelines, recommendations and standards updates

The engineering planning, design, demanding construction and supervision, painstaking commissioning and troubleshooting, and meticulous operation and control involve numerous challenges. Thousands of details must be well conceived, accurately executed, and carefully coordinated for a project to achieve economic, social, technical and environmental success. Overlooking or poorly integrating such details can cause great complications. One such vital detail is hydraulic design and particularly waterhammer and vibrations; hydraulic vibrations, hydraulic transients and water column separation and rejoinder phenomena have caused many troubles and accidents. Reflections on actual events in such systems lead to vital lessons for future safe and effective design. In hydro plants with long tailrace tunnels, the minimum pressure at the downstream of turbine runner, resulting from load rejection or other transient events, can seriously damage or impair both the turbine assembly and the water conveyance system.

Reliable knowledge of all loads acting upon a system is the key to safe hydraulic system design. The most dangerous stresses are those provoked by pressure surge and vibrations; the worst of these is the occurrence of resonances and instability. Maximum pressure during transient events, such as those associated with rapid closing and opening of wicket gates, can break equipment and even in extreme cases result in injury and death. Sound design of a new plant is impossible without a complete analysis of transient events. Transient analysis also helps to prevent resonance in existing plants and thus increases the reliability of plants and reduces their operating and maintenance costs.

The costs associated with cavitation, transient conditions, vibrations and stress analysis for mini, small and big hydroelectric plants are often quite comparable in absolute values; thus the relative cost, as a fraction of the total investment, is obviously much greater for smaller plants. Such analysis costs in large plants usually entail less than one percent of the total, whereas these costs can be a sizable fraction of the overall expenses in some small plants. Though suffering from the same problems as the large ones, there is a dangerous though understandable tendency to simplify analysis and review process for reducing the design costs of small plants. The net result is that there tends to be higher risks in smaller plants [18]. Guidelines, recommendations and standards have needed updates and modernization to support quality and safety.

Pumped-storage (and conventional hydro storages) are of paramount importance as they are the most reliable and affordable energy storages for accommodating intermittent renewable generators in the power grid, also providing ancillary services as readily adjustable stand-by and running reserve for nuclear and other thermal generators. However, large hydro facilities require a large amount of capital investment, so their design, construction and operation needs to be well conceived, executed and coordinated, if they are to achieve the safe and economical operation. The challenges of high-head typical of pump-storage further complicate system design. This fact, together with cost stress on the construction, equipment and labor, justifies the need for more rational design of new pumped storage plants. That is, the system components should be strained as close to the allowable limits as possible, without endangering the safety.

2. Death and disaster lurks in zones of instability

2.1. Bajina Basta discovered “S” instability in 1970s

For a low-specific-speed (high-head) reversible pump-turbine in the pumped storage plant, shown in Figure 1 owing to their “S” shaped turbine characteristics, the operations are unstable near or at runaway conditions, leading to oscillations characterized by large pressure fluctuations and transients as the system passes through the unstable dangerous zone [7][8][10][20][21]. The analysis of transients is rather a complex and time consuming task, each case introducing some new problems.

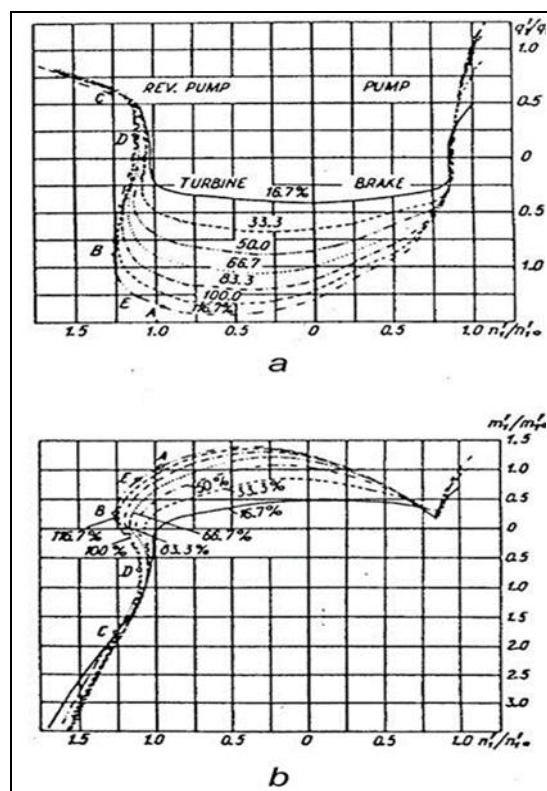


Figure 1 Bajina Basta pump-turbine dimensionless "S" form unstable

manufacturers have empirical pressure and velocity distribution data for their machines [9], and others have measured data from model turbine draft tubes [4], but this work is not yet codified into guidelines, recommendations or standards. All the data for each machine in a plant must be carefully evaluated because the similarity laws do not apply to two-phase flows [4][14].

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. 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.

2.2. Description of instability

High-head reversible pump-turbines (low-specific-speed) have an unusual characteristic in turbine operating modes: unlike typical behaviour, beyond the runaway zone, any decrease in speed reduces the discharge. In a unit speed – unit discharge, n'_1 - q'_1 diagram partial load curves for a pump-turbine are markedly "S" shaped, as shown in Figure 1. In this runaway zone the flow through the runner is highly complex: the water near the bend separates, flowing toward the turbine outlet into the draft tube, while the water near the crown goes opposite way - towards the wicket gates. The net discharge might be either negative (turbine) or positive (pump). These operating modes are, naturally

Our experience of "S" form instability and hydraulic resonance, gathered from pumped-storage plant Bajina Basta in Serbia (previously, Yugoslavia), the plant endangered by hydraulic transients, is reviewed to point out possible dangerous mistakes and importance of updating guidelines on safety. Transient analyses were exercised at all design levels of Bajina Basta (i.e., during feasibility studies, general design and detailed design¹) plant by both the design team (led by the first author) and the manufacturer (Toshiba). The "S" type instability was discovered and first publicly reported during 1974-1976 [20], while the numerical instability of computer program in the "S" zone is discussed recently for the first time in the paper [22].

In order to avoid the danger of water column separation and consequent reverse waterhammer, intensified by "S" instability, the minimum pressure in any conduit (tunnel, penstock, pipeline), as a design criterion, should not fall below 50 kPa (0.5 bar), even temporarily [1][12][15][16]. 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 for vertical shaft units. Descriptions and preventions of these phenomena (see article [17] (published in this proceedings). Some

¹ Transient analyses should (must) be done before any reconstruction particularly enlargement and/or increase of discharge – power.

accompanied with violent vibrations and highly developed cavitation [3][13][21]. Running through this zone cannot be prevented. Nevertheless, such machines are needed and rapidly developed towards higher head and greater unit power. The pump-storage power plant "Bajina Basta" shown in Figure 2 has two pump-turbines configured to form a hydraulic loop. This arrangement is motivated by cost savings but in the long run is mistake, particularly when associated with typical "S" type instabilities. Ideally, each pump-turbine should have its own hydraulic waterway in spite of the higher initial price.

The numerical simulations exhibited intensive instability and resonance, though the accuracy of analysis is "reasonably" should be carefully verified.

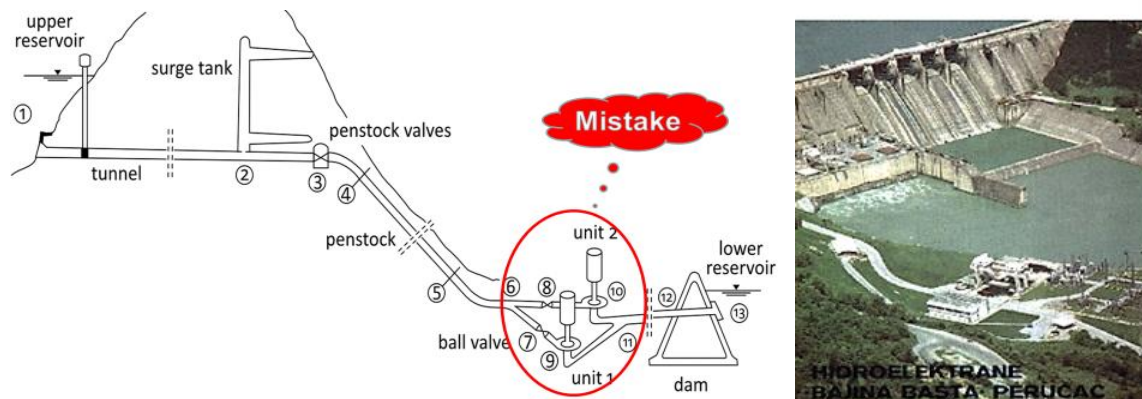


Figure 2 Two pump-turbines in the loop Bajina Basta mistake

To discuss the pump-turbine model characteristics, the unit speed, unit flow and unit hydraulic torque are defined as: $n'_1 = \frac{nD}{\sqrt{H}}$; $q'_1 = \frac{Q}{D^2\sqrt{H}}$; $m'_1 = \frac{M_h}{D^3H}$, M_h is the hydraulic torque, n - rotational speed, D - turbine diameter, H - net head, and Q - discharge. In the "S" zone three discharge values of (dimensionless q'_1/q'_{10}) two negative and one positive, correspond to one value of speed (dimensionless n'_1/n'_{10}); also three torques (dimensionless m'_1/m'_{10}), two positive and one negative, correspond to one value of n'_1/n'_{10} . Such multi-valued nature would result in a difficulty in application of these curves to transient simulation. In reality this means sudden change of torque accelerating the generator's shaft,

At the time of load rejection the generator is disconnected of the grid, neglecting mechanical and generator losses, the "S" type instability is described by transformed equation of rotating masses $Jd\omega/dt = M_h$, here J is the moment of inertia of rotating parts and ω angular speed

$$J \frac{\pi}{30} \frac{dn'_1}{dt} = -m'_1 D^4 \sqrt{H},$$

A simple description of "S" instability, as not published in journals, guidelines, recommendations and standards, is here repeated [20][22].

If the transient phenomenon begins at point A, in Figure 1, a normal turbine operation and the gate opening is not changing, n'_1 goes down ($dn'_1/dt < 0$) to point B since $m'_1 > 0$ (Figure 1b). At point B $m'_1 > 0$, however, when $n'_1 < n'_{1B}$ the working point jumps from B to point C. At this moment $m'_1 < 0$ and m'_1 goes up to point D. At point D $m'_{1D} < 0$ and when we have $n'_1 > n'_{1D}$ the working point jumps from point D to point E, where $m'_1 > 0$. The process will be repeated passing through the points EBCDE and will never stop. Due to the waterhammer in the penstock and tailrace tunnel the head is changing quickly, which results in the operation passing through point B and D in the zone between B and D, as well as in the zone of $n'_1 < n'_{1C}$ and a new passage to the zone of $n'_1 > n'_{1E}$. Thus, all type of operations shown by the four-quadrant characteristics is possible. This nature of pump-turbine curves bring about the sudden changes in pressure, discharge, speed of rotation and torque with unpredictable superposition of pressure fluctuation, followed with resonance. Jumping from point B to point C, flow direction changes suddenly from turbine mode ($Q < 0$) to reverse pump mode ($Q > 0$),

quadrant IV zone, and then from point D to point E back to the turbine flow direction. In this zone computer programs deliver uncertain and inaccurate results.

2.3. Site tests in 1983 confirmed changing of flow direction

Field tests carried out in February 1983 measured jumping from turbine to pump discharge direction and back in turbine flow. This zone marked in Figure 3a by RP (reverse pump). In Figure 3c trajectory of unit 1 cut twice the zero flow line dividing pump and turbine direction of flow.

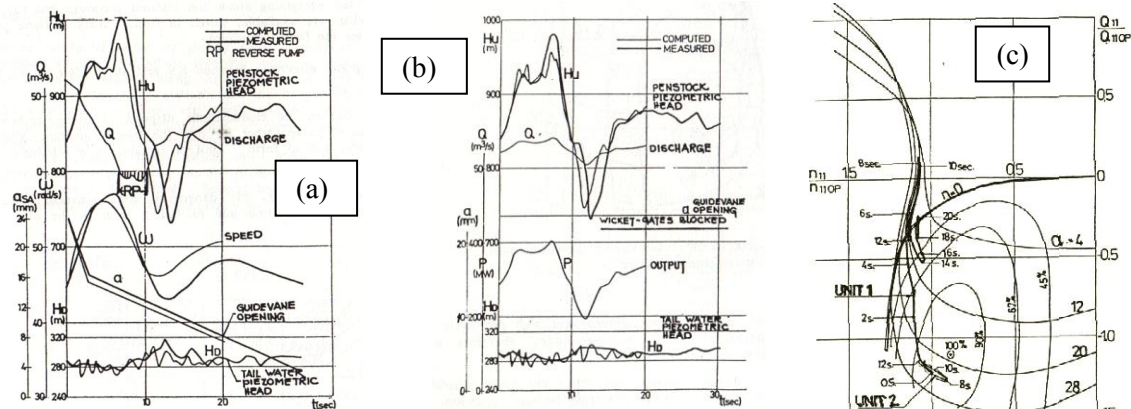


Figure 3 Pumped storage plant "Bajina Basta". Unit 1 load rejection; Unit 2 connected to the grid. (a) and (b) Comparison between measurement and calculation, (c) Both units trajectory in model hill chart

The testing procedure was:

- both units 1 & 2 operated as turbines, developing 298 MW each;
- Unit 1 dropped out and its wicket gates closed down rapidly;
- Unit 2 remained operational in spite of violent pressure surges.
- The discharge could not be measured.

Figure 3a displays the changes in Unit 1 which has dropped out. The wicket-gates remained open for some 0.2-0.3 s and then started to close down as prescribed, first rapidly and later slowly. The other lines represent other variables: pressures in the spiral casing H_U and in the draft tube H_D , angular speed ω , flow Q , and guide vane opening a . Figure 3b shows pressure variations in Unit 2 which remained connected to the system with $\omega \approx$ constant and wicket-gates blocked in the open position $a =$ constant. The other lines are, respectively, the pressure in the spiral casing H_U and in the draft tube H_D , flow Q and output P .

2.4. Accuracy and instability uncertainty

The agreement between measured and computed values is "reasonable," although no calibration was carried out. (At design stages there is no calibration.) However, some details are clearly visible:

- Figure 3a and b show big difference in measured and calculated maximum pressure. Measured much greater.
- wave velocity used for computation is slightly greater than the real one (comparing peaks in Figure 3a and b);
- full-sized prototype machine is different from the model, it is relatively stronger and more efficient (comparing peaks of maximum rotational speed in Figure 3a and b). The results showed that Unit 1 did enter the fourth quadrant. Discharge Q was negative (pump direction) between 6.9 and 10.3 s after power failure (RP zone). These results are also plotted in Figure 3c in the characteristic diagram of pump-turbine. Unit 1 follows the "S" shaped curve rather far in the fourth quadrant, goes back under the curve of zero efficiency, and so forth. Unit 2 remains in a relatively narrow range around the initial operating point. Thus, the machine enters this dangerous zone (reverse pump operation) characterized with strong vibrations, hydraulic unstable vortices, multiphase cavitation, all much more severe than in normal operation.

- Long variable period of measured pressure fluctuation indicates that a void in the draft tube is acting as a closed surge tank (air vessel) all the time. The largest period of $T = 9 - 5 = 4$ s is followed with the time interval of runner filling with water $\Delta t = 12 - 7 = 5$ s, and rejoinder of separated water columns at peak pressure. Then a new void is formed, as shown in Figure 3a.
- The Unit 2, continuing operation, as shown in Figure 3b, also had a void all the time, with longest period of $T = 18 - 7 = 11$ s for the maximum pressure without a peak; the air in the draft tube cone is compressed but occurred without a sharp pressure peak: rejoinder of separated columns was mild and incomplete.
- Huge pressure fluctuation in the draft tube and penstock are measured as shown in Figure 4a
- Figure 4b made from Figure 4a shows that the transient traces at full load rejection are different, but compare to the 3/4 load rejection, presented in Figure 5b, completely unlike. In the first case, noticeable difference is after 14 s, while in the second case are makeable after 8 s. Physical instability is the reason for waviness of all lines. Different maximum peaks in the penstock pressure and minimums in draft tube pressure are evident in Figure 5a.
- Comparing site tests and calculations in Figure 5b and Figure 6 it is clear that mathematical instability add more instability as the result of uncertainty and inaccuracy. Results of tests and calculations must be carefully analyzed by experienced experts.

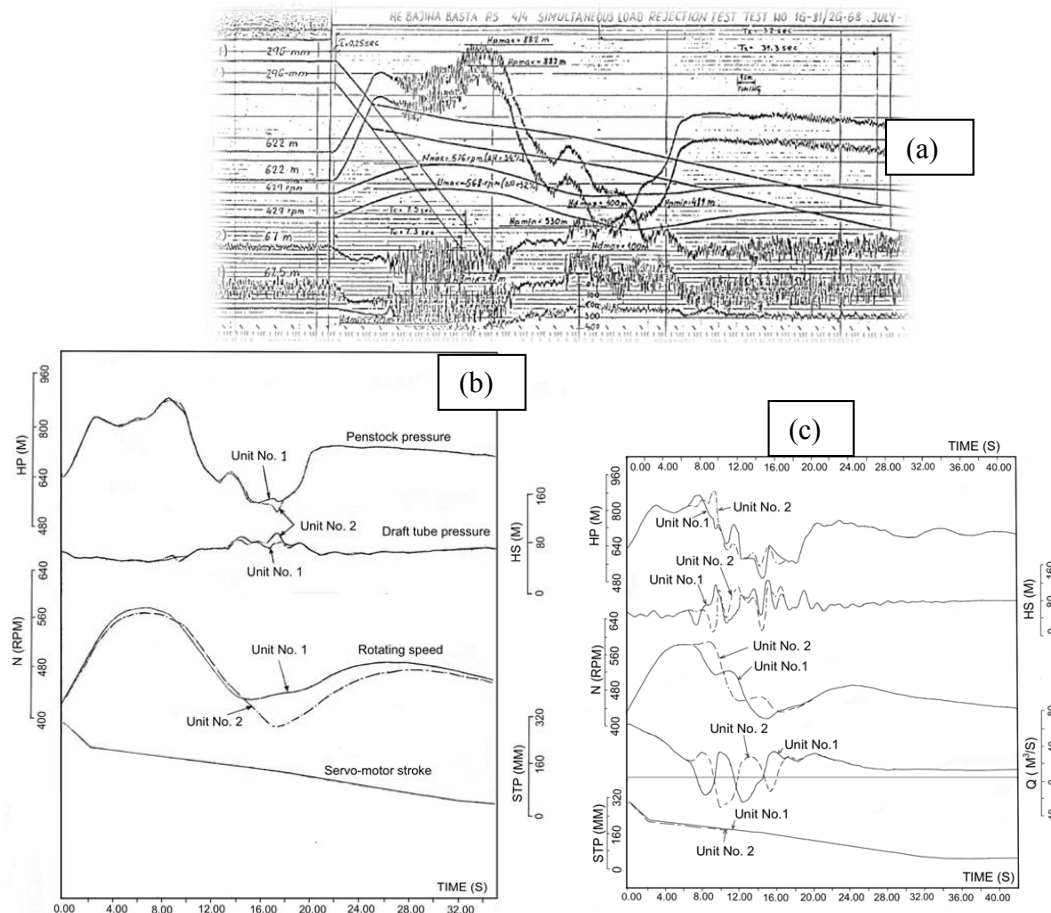


Figure 4 Simultaneous two units load rejection from full capacity (2x298 MW). (a) Copy of originally measured strip chart in 1980s. (b) Site test results. Simultaneous load rejection from full load generation. (c) Calculation results corresponding to simultaneous load rejection from full generation.

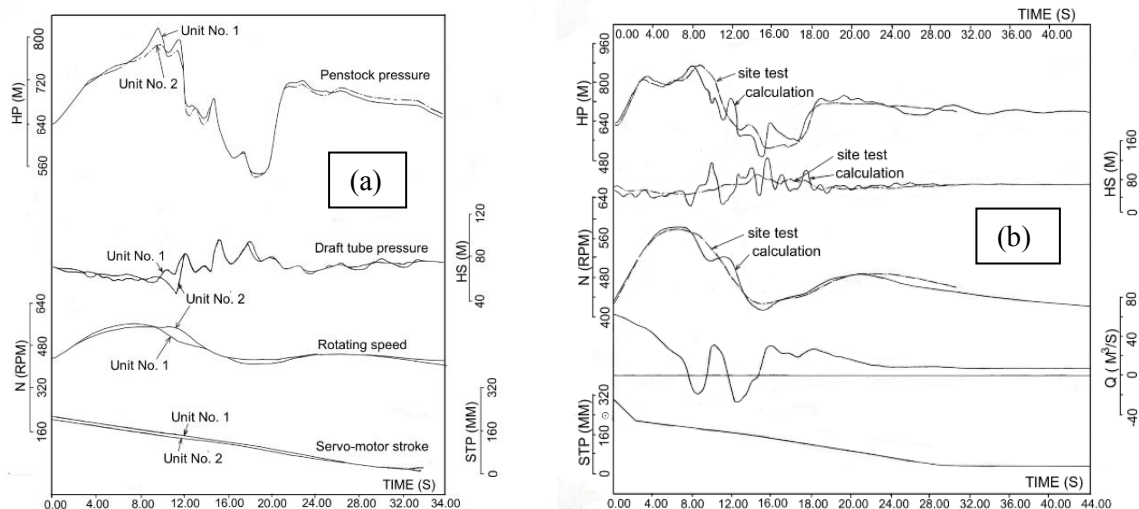


Figure 5 (a) Site test results. Simultaneous two units load rejection from 3/4 load generation
(b) Comparison of calculation and site test for unit 1 at simultaneous two units load rejection from full capacity (2x298 MW)

In this example the designers identified and verified dangerous instability. The control system was thus altered to prevent two units simultaneous runaway which was the most catastrophic case of concern. The probability that all four protecting devices – two spherical valves and two guide vanes – might fail to close is very small. But some risk will inevitable still be present.

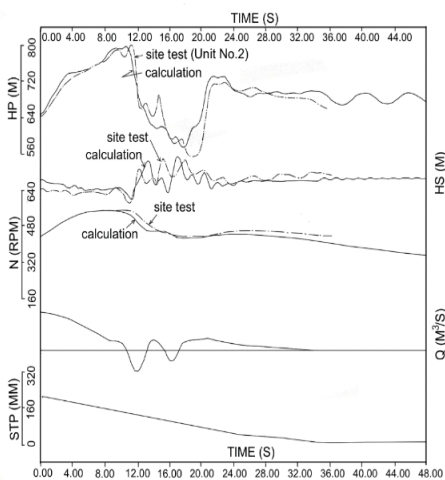


Figure 6 Comparison of calculation and site test at simultaneous two units load rejection from 3/4 load

2.5. Recent numerical analysis at “S” instability

The calculation shown in Figure 3 has been repeated and graph constructed with smaller time step to better analyse the unstable “S” zone. A sharp peak at maximum penstock pressure shown in Figure 7 shows the instability. This corresponds to the unstable zone in diagrams of Figure 1; the single value of rotational speed (n'_1/n'_{10}) corresponds to three discharge (q'_1/q'_{10}), and three torque values (m'_1/m'_{10}). Interestingly, changing the moment of inertia from $1.500 \times 10^6 \text{ kgm}^2$ to $1.502 \times 10^6 \text{ kgm}^2$ less than 0.2%, the unstable peak shifts to entirely different shapes as shown in Figure 8. To better understand this, the “S” phenomenon should be analysed both theoretically and in laboratory. Computer simulation and mathematical analyses in such cases are approximate and uncertain!

Actually existing instability excitation in the hydraulic system causes problems, accidents and disasters. Results of calculation delivered by computers are inaccurate and even wrong. This is evident in Figure 7 and Figure 8.

2.6. Bajina Basta calculations in 1970s and “S” instability

Simultaneous full load rejection of two units and one unit with wicket-gates blocked in an open position respectively shown in Figure 9a and Figure 9b present the instability of the “S” shaped pump-turbine characteristics in the runaway zone. These phenomena were described by Pejovic at al. [20]. These results were initially viewed as so dramatic because only a few believed that a machine could

enter the fourth quadrant; so some kind of verification was needed (1975). When the plant was finally completed (1982) the field tests fully confirmed the “S” instability.

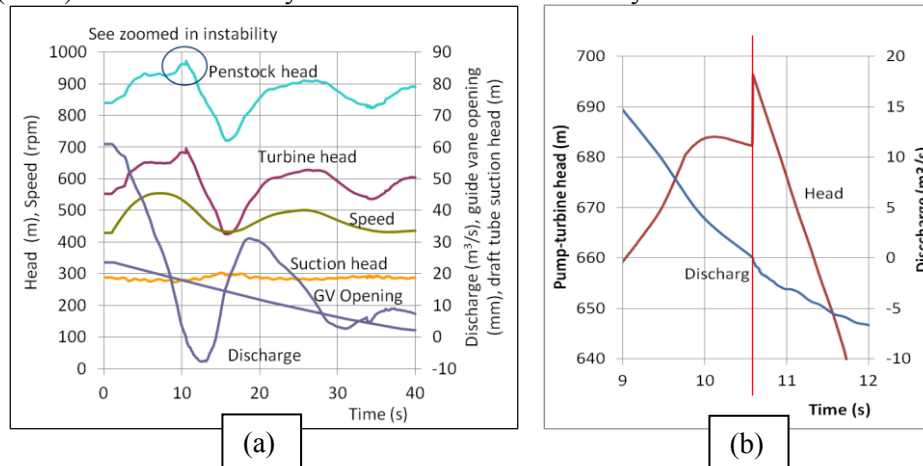


Figure 7 "Bajina Basta" pumped storage plant load rejection. Both penstock pressure and pump-turbine head have unrealistic peaks (a). Magnified head and discharge curves (b) show that this peaks correspond to the zone of instability; discharge just change from generating into pumping direction.

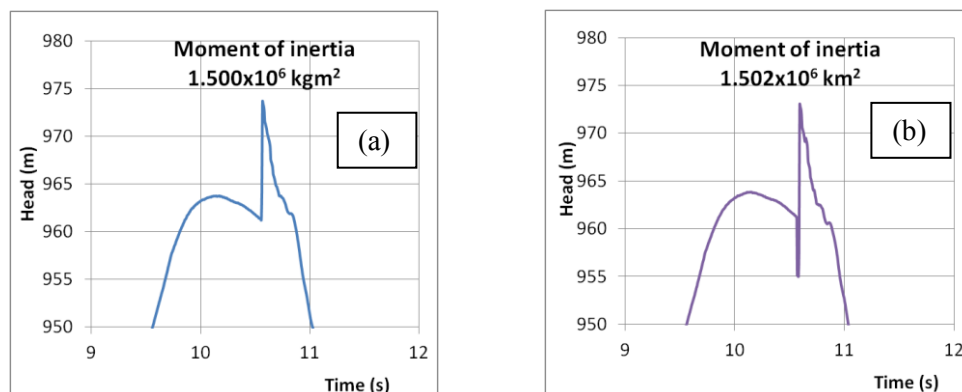


Figure 8 Changing moment of inertia for less than 0.2% leading to uncertain shapes and instability of pressure peaks

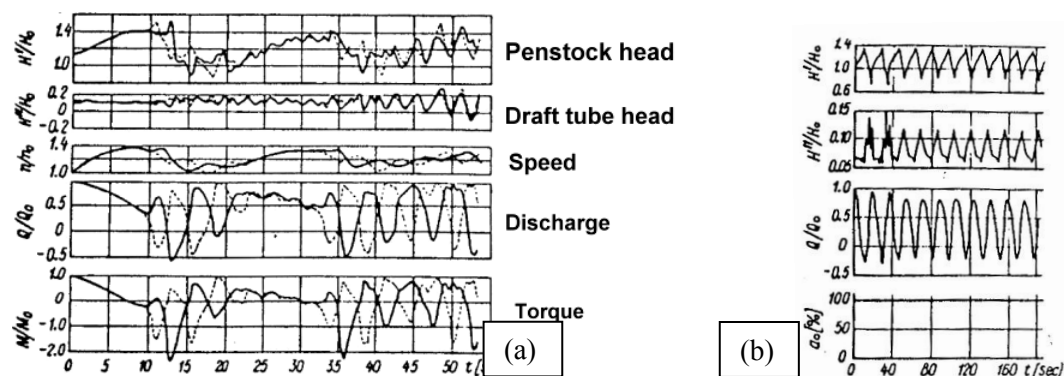


Figure 9 Waterhammer calculation; (a) two units' runaway simultaneously; guide vanes and inlet penstock valves are open; both pump-turbines run at full runaway; calculated zero pressure in the turbine draft tubes means water column separation (b) one unit load rejection

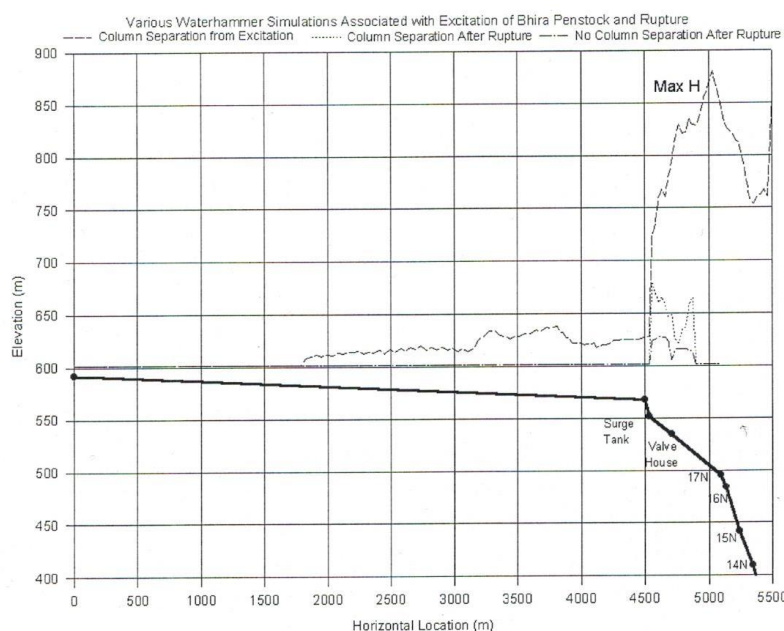


Figure 10 Maximum pressure (HGL) and waterway simplified scheme

water column separation during runaway remained unnoticed as extremely dangerous by the design team (Pejovic was one member of the team), neither had it been indicated by turbine manufacturers nor other experts involved in the design and construction of the plant. Fortunately, the problem was resolved by preventing the turbine running through the unstable “S” zone of transient operation.

The response of load rejection from one unit and its resulting runaway are shown in Figure 9b [20][21]. The amplitude of pressure fluctuation in the draft tube, H'' , is as high as ± 3 bar, at the inlet, H' , up to ± 18 bar, and the discharge is jumping from turbine to pump direction.

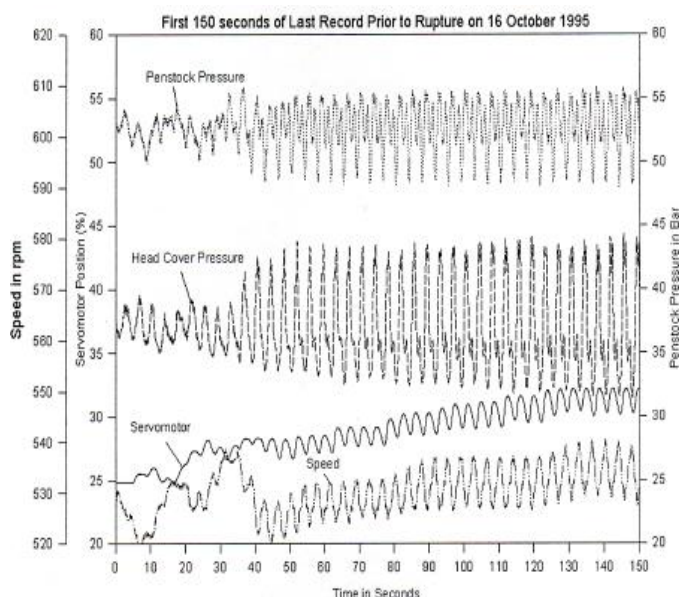


Figure 11 measured data prior to penstock rupture

The peaks of pressure fluctuations exceeded 900 m, the design penstock pressure head. Therefore, the governing and protective system had been changed to prevent parallel runaway of both units to minimize the risk of a catastrophic accident. The problem was solved by ensuring that any of the four protective devices respond to all critical transients [13]. Though it is highly improbable that all four closing devices jointly fail, careful maintenance must ensure their continuous operation.

The design team of this power plant carefully analysed hydraulic transients and discovered a dangerous “S” form instability. However, the

3. Bhira plant accident in 1995 four dead

The Bhira Pumped Storage pump-turbine has “S” unstable four-quadrant characteristics from model tests similar to Figure 1 Bajina Basta pump-turbine dimensionless “S” form unstable characteristics. The waterway and transient simulations are in Figure 10. As the result of running into unstable zone penstock pressure, long dashed line in Figure 10, has been very high. After rupture pressure could be also high and should be controlled to prevent further troubles. Two lines, dotted and dot-dashed in Figure 10, ended at the rupture represent two different calculated scenarios. Records prior to rupture depicted in Figure 11 show how the amplitudes increase in time approaching maximums. [7]

It has been informally reported that four people died as a result of a pipeline burst, but have not been able to confirm this.

4. Conclusions

Mathematical modelling is certainly a valuable and efficient "tool" for analysing hydraulic transients, stability and resonance in hydroelectric plants and other hydraulic systems. In the case of instabilities such as high head pumped storage hydroelectric plants ("S"-shaped pump-turbine characteristics) the results are uncertain and inaccurate and must be carefully analysed by experienced experts.

It is fair to admit that those who design and construct complex 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. 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. The over-riding duty of engineers is to act in the best interest of both clients and the public [9]. Updated guidelines recommendations, and standards help designers, owners, and decision makers what should be done systems to be as safe as possible.

Certainly the design and operation of any power system requires a delicate balance between certain competitive objectives. One crucial issue is related to the phenomenon of "S" unstable machine characteristics. Run into unstable zone is dangerous; behaviours are unpredictable. Results of calculations are uncertain and inaccurate. Careful analyse inevitable. The "S" instability is not the only dangerous phenomena to be analysed and resolved.

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