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Water Column Separation at Turbine Start up Loading

Pejovic S.¹, Gajic A.²

¹ 300 Webb Drive, Mississauga, Ontario, Canada, L5B 3W3

² Academy of Engineering Sciences of Serbia, Kraljice Marije 16, Belgrade 11000, Serbia

¹ Email: pejovic.stan@gmail.com, ² agajicprof@gmail.com

Abstract. According to authors knowledge this is the first case of water column separation that happened, not during load rejection, but during the turbine start and loading to full power output. To control the transient flows in water courses, the wicket gates of turbine are the primary flow regulators. The minimum pressure during transient operations of hydroelectric turbine units may cause a water column separation and the subsequent re-joining creates forces that could damage turbine runners, non-rotating parts, and the whole machine house. This condition occurs when a local pressure drops below the vapour pressure or partial pressure of gases (air). The instant pressure rises from collapse of voids have the potential to crack internal linings of water conductors and connections between steel and concrete, and may damage hydraulic machines, air valves, penstock valves, or gates. The damage may not be evident immediately but would be observed after repetitive transients. All calculations and measurements of transients must be completed for analysis of the water column separation, following existing guidelines, though there is no standards and recommendation on the subject of waterhammer and hydraulic vibrations. This paper presents an approximate analysis of water column separation based on the pressures measured on site.

1. Introduction

One specific event, water column separation at turbine start up loading, deserves special attention. This is the first case of reverse waterhammer happened, not during load rejection, but during the turbine start to full power output. In hydropower plants the minimum pressure downstream of the turbine runner triggered by transients, may cause water column separation, and subsequent rejoinder to occur in the draft tube. Such events have potentially severe consequences for both the machine and the water conveyance system. This article overviews these important issues.

There is a strong tendency for some engineers, managers, and owners to focus attention on steady operating conditions and on non-technical aspects of plant designs. This practice implicitly relegates hydraulic transients, vibrations and resonance, and particularly what comes after the turbine (namely, the draft tube and tailrace) to an afterthought. Yet such an approach is dangerous, as many important and potentially destructive hydraulic phenomena occur in, or as a result of, the draft tube, draft tube extension, or pressurized tailrace tunnel. (The term tailrace tunnel may connote either an open channel conduit or a pressurized conduit. As used herein, it refers to the later.)

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Flow in the draft tube is multiphase, fully three dimensional, unsymmetrical, pulsating, or has an unstable rotating unsymmetrical vortex core at its middle. Therefore void containing gasses and vapor is always present and must be carefully analyzed and dangerous water column separation prevented. Cases must be carefully evaluated. It cannot be emphasized too strongly that water column separation represents a serious risk to the performance, stability, safety and economics of hydro systems. Catastrophes had occurred [2](Figure 11 page 41 in Reference [2]). In most cases separation and reverse waterhammer caused the accidents [4][5][6][7].

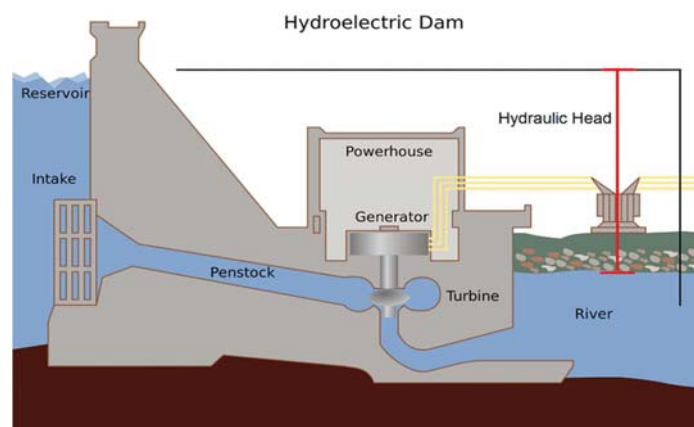


Figure 1 Scheme of hydro power plant

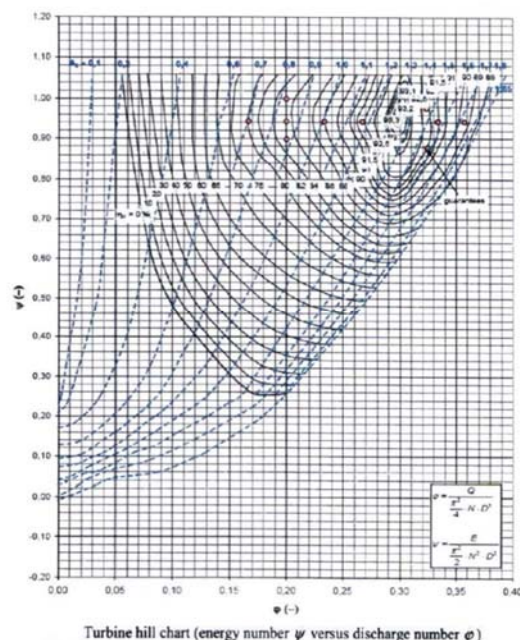


Figure 2 Turbine hill chart

Medium head run-on-river hydropower plant (Figure 1) has limited zone of operations. This plant had strong problems with high vibrations in both partially and full load. Because of that, commissioning tests were extended. The Hill Chart provided by model tests is shown in (Figure 2). [10]. Hydraulic transient and vibration analyses are simplified applied fluid mechanics for practical applications, computational fluid dynamics (CFD), and other solutions, only roughly describe the flow. Therefore, all calculations must be carefully verified on site [2][6].

Electrical power produced by the gravitational force flowing water from an upper reservoir through a turbine down into a lower reservoir is the most widely used form of clean renewable energy. About 20% of total energy production in the World is from water energy. It is the most widely used form of clean renewable electricity storage. Worldwide 99% of electricity storage is hydro storages [2][8][9].

Wind, solar, and run-on-river plants are variable sources of electricity. Hydro and pumped storage plants are the only clean electricity storage; therefore must be properly designed to properly respond to sudden changes in electricity consumptions.

2. Water Column Separation in the Draft Tube during Turbine Closure

The length of tailrace tunnel as a function of closing time of guide vanes and flow speed in the draft tube, and tunnel, in order to avoid the water column separation, can be calculated through an approximate equation based on field experience:

$$L = k \frac{gT_s}{2v_o} \left(8 - \frac{v_{dt}^2}{2g} - h_s \right) , \quad (1)$$

where: L = permitted length of tailrace tunnel, T_s = closing time of guide vanes, $k = 0.6$ to 0.7 empirical coefficient, v_{dt} = water speed at the runner outlet - the draft tube cone inlet, h_s = suction head v_o = flow velocity in the tailrace tunnel.

This approximate equation is based on the rigid water theory neglecting the elasticity [1][2].

Applied to the turbine wicket gates closing law (): $T_s = 4$ s time of guide vanes closure, $k = 0.6$ empirical coefficients, $v_{dt} = 9.6$ m/s water speed at the runner outlet - the draft tube cone inlet, $h_s = 0.1$ m suction head, $v_o = 4.1$ m/s flow velocity in the equivalent cross-section of the draft tube.

$$L = 22 \text{ m.}$$

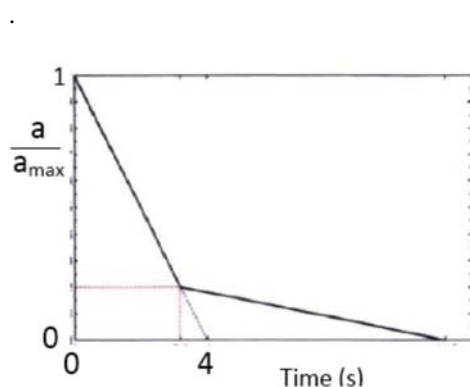


Figure 3 Wicket gates closing law

The length of the tailrace tunnel is ≈ 18 m < 22 m; water column separation in the draft tube will not occur, but as accuracy is very small, therefore detailed analysis is recommended, and concluded that dangerous water column separation and re-join must be avoided under any operating conditions. This method of calculation is appropriate to analyse the issue for water column separation at the level of Feasibility Study, and General Design [3] when manufacturers are not yet selected.

2.1. Uncertainty

The servomotor speed depends on oil viscosity and temperature, the state of the mechanism, the quality of maintenance, etc. All these external factors have to be considered even in the design phase. To allow for variability in closure timing, length of the tailrace tunnel calculations should be made using 10% faster closing [3]. The scaled down closing time

$$T_{sd} = 0.9 T_s = 3.6 \text{ s.}$$

Applying Equation (1) the permitted length of the draft tube is

$$L_{sd} = 12 \text{ m.}$$

The length of the tailrace tunnel is $\approx 18 \text{ m} > 12 \text{ m}$; water column separation in the draft tube will occur.

3. Measured Water Column Separation

According to long time authors' experiences water column separation usually occur after quick shut down [4][5][6][7]. Acquisition and visualization of a wide variety of measured variables, monitor the plant systems, save measured data, and should notify responsible specialist personnel in the event of a malfunction.

In this circumstance, response and alerting is of particular importance

This raises difficulties of whether system sort out actions, forwards them to the responsible persons, and alerts them.

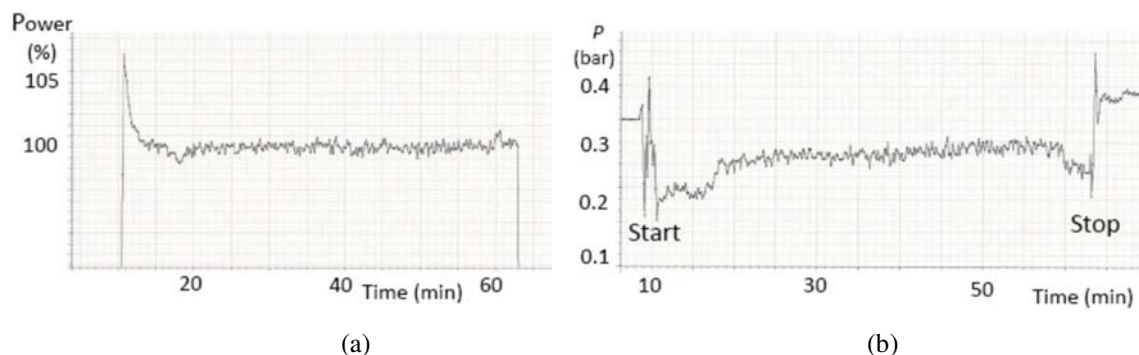


Figure 4 (a) measured power output, (b) draft tube pressure from acquisition system

Figure 4 shows the start, normal operation, and normal shutdown of the middle head hydraulic turbine; (a) power output, (b) pressure measured on the draft tube cone. Turbine net head varies between 37 m and 43 m, Power output between 8 MW and 20 MW. Both at the start and the stop water column separation, and reverse water hammer occurred followed by sudden pressure jumps!.

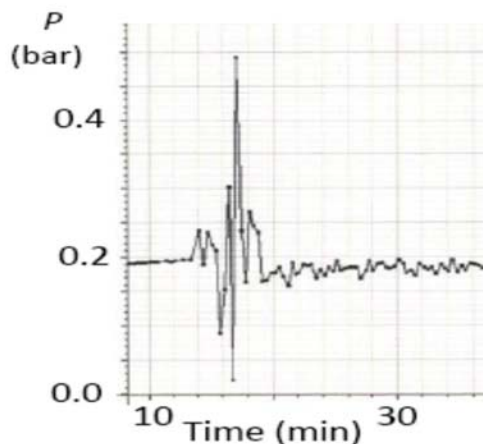


Figure 5 Draft tube pressure measured some other day

Minimum pressure on the draft tube cone is close to zero, but in the middle is an empty space (air and vapour). Returning water run into the runner blades; pressure jumps up.

4. Turbine Submergence

Solving Eq. (1), suction head reads

$$h_s = 8 - \frac{v_{dt}^2}{2g} - \frac{2v_0 L}{kgT_s} = -3.6 \text{ m} . \quad (2)$$

The calculated submergence is few meters greater than it is. As the applied equations (1) and (2) are approximate detailed analyses must be completed [2]. Figure 4 shows the turbine start, overload, and immediate power drop to rated power output. Quick guide wanes closing from overload to full load is followed by water column separation and rejoinder of separated water columns.

The second pressure drop in is close to zero (1 0.03 11 11). The second pressure maximum is 0.5 bar. It is important to point out that this problem could be easy solved adjusting the governor and control system.

5. On Site Acquisition Data

This plant is long time in operation but nobody noticed this very dangerous phenomena. Probability serious accident to occur is very high. The turbine and generator are exposed to water hammer shocks, vibrations, and fatigue; at least maintenance costs are highly increased.

Saved onsite measured data (diagrams) must be frequently analysed by experienced experts. Hydraulic transients (waterhammer, vibrations, resonance) only high experienced experts in reading site diagrams could understand, notice, and discover dangerous anomalies, and solve these problems. Most companies, equipment manufacturers, and designers do not have such experts••specialists, educated, and experienced to understand and solve such problems; prevent accident; increase safety.

Decision makers (in Canada provincial Ministers and Governments and in many other countries ministers as well), managers, hydro plans owners must be aware of such dangerous accidents and hire knowledgeable, experienced expert(s) to provide hydro plants safety. If not, incidents and catastrophes will happen again.

6. Conclusions

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. Although this paper discusses specific case, 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, this issue did not arise before, but will arise, until the associated challenges are brought more consciously into the open where they can be discussed and debated. The duty of engineers is to act in the best interest of clients and the public.

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 water column separation in tailrace tunnel, particularly following a transient turbine operation (e.g., start, load up, load down, load rejection, emergency closure, runaway, etc).

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 controllers' dexterity and skill, and it must be carefully designed, tested, and maintained. It also does not rectify shortcomings of inadequate submergence or defects in other design criteria, which are, in part, revealed through thoughtful case studies of actual events in operational facilities.

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