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Temporal interaction of water hammer factors during the load rejection regimes in a hydropower plant equipped with Francis turbines

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Abstract. The refurbishment of the hydropower plant aims to upgrade the performance, in particular on the availability and safety of the units. The transient regimes (e.g. start-up procedure, load rejection, speed-no-load, and so on) shorten the lifetime, raise the maintenance requirement and cause a loss of energy production. Therefore, the objective of this study is the analysis of the temporal interaction between the factors during the load rejection of the Francis turbines. The approach aims to identify transient hydrodynamic phenomena, especially in the framework of operating hydropower units equipped with Francis turbines as main regulating factor for the electrical grid. The investigations focus on evaluating the maximum pressure generated in the hydraulic pathway and comparing them with the admissible pressure value. Thus, the influence of certain physical factors identified in the flow passing through the turbine operated in transient regimes is explored. Also, the effect of some operating parameters of the hydropower plant on water hammer generation was examined. The investigation is based on the analysis of the experimental data connected with the analytical calculation of the maximum overpressure and a numerical simulation of the temporal interaction between the factors. The phenomena associated with the emergency shutdown (load rejection) of the Francis turbine from different wicket gate openings (e.g. 100%, 75%, 50% and 25%WG) considering the same wicket gate closing slope are analysed. The conclusions are drawn in the last section together with a few recommendations to reduce the overpressure with a direct impact on the required maintenance, lifetime of the hydropower unit and the safe operation of the equipment.

1. Introduction

Lately, with the emergence of different alternative energies (e.g. photovoltaic panels, wind turbines) the requirement for the electrical grid has changed considerably. Consequently, Hydraulic Power Generators (HPG) are often requested for operation in peaking in order to stabilize the grid parameters and to compensate the unavailability and inflexibility of these alternative resources [3].

In order to equilibrate the grid, the HPG are operated more often in transient regimes (e.g. start-up procedure, load rejection, speed-no-load, and so on) leading to a diminished lifetime of the units [1], increased operational costs and additional power generation losses [2]. To meet these challenges, the modernization of hydropower plants (HPP) fleets strategically aims to improve production capacity,

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availability and operational security. Also, the operating procedures and parameters of the HPG units have to be adapted to take into account these additional requirements to avoid premature equipment degradation [4].

All these requirements lead to the necessity to know and estimate the additional Hydraulic Passage (HYP) loads resulting from HPG operation in transient regimes in order to comply with the allowable limits. One of the most important loads occurring in HYP during transient regimes is the overpressure peaks resulting during the water hammer phenomenon [5]. The maximum values are influenced by the temporal interaction of the factors contributing to the water hammer pressure surge. This study aims to analyze this interaction for a selected case in order to identify the contribution and the precedence of the main factors influencing overpressure peaks in HYP. A HPP equipped with Francis turbines from Hydro-Quebec fleet is considered as case study [6].

The methodology is based on analysis of factors using three approaches: experimental, analytical and numerical. This study aims to analyse and estimate the behaviour for a Francis unit during emergency shutdown (triggered by load rejection) under a wicket gates closing time (tBAF) of 15 seconds for a full stroke, as follows: the interaction of different factors was identified based on existing experimental data in Section 2; the maximal values for overpressure were calculated using an analytical model in Section 3 and the behaviour in time was simulated using ALLIEVI software in Section 4. Afterwards, a comparison of the calculated values against the trend observed for the experimental data makes it possible to identify the agreement of the results in Section 5, as well as to assess the accuracy and limits of the considered approaches. Finally, the conclusions as well as few perspectives are highlighted in the last section.

2. Experimental investigations

The subject of the interaction in time of water hammer factors was preliminary explored during the test campaign conducted on 24 HPG configurations of the Hydro-Québec HPP fleet [6]. The actual study is focused on the overpressure time evolution during load rejection procedure at different wicket gate openings (%WG), (e.g. 100%, 75%, 50% and 25%) considering the same WG closing slope [7].

The maximum overpressure (dP) at the spiral casing inlet section during 100%WG load rejection under tBAF of 15 seconds was measured on site during the test campaign and it is noted in Table 1. The maximum overpressure values (dP) corresponding to 75%, 50% and 25%WG load rejection under tBAF of 15 seconds are not available from the experimental investigations for the actual study. As a result, a crude estimation of these values is performed for this tBAF according to the documented HPG tendency [6]. Based on experimental data measured at 100%WG for tBAF = 15 seconds, respectively tBAF = 7.75 seconds, the ratio of the overpressure (dP) diminution was obtained: r = 1808 kPa / 1694 kPa = 0.9369. Afterwards, the maximum overpressure (dP) values corresponding to 75%, 50% and 25%WG for tBAF = 15 seconds are calculated by multiplying by the ratio r = 0.9369 the reference experimental data (dP) for tBAF = 7.75 seconds (i.e. 1800, 1753 and 1558 kPa). These results are listed also in Table 1 with the symbol ($^{\pm}$).These values are used to validate the results obtained by the analytical and numerical approach.

Table 1. Maximum overpressure values during load rejection for tBAF = 15 seconds and different WG openings of a Francis turbine (**experimental data** and calculated values with $^{\pm}$ symbol).

WG opening	Maximum measured pressure	
(%)	(kPa)	(mwc) *meter water column*
100	**1694**	**172,7**
75	1686 $^{\pm}$	171,9
50	1642 $^{\pm}$	167,4
25	1460 $^{\pm}$	148,9

The time evolution of the parameters recorded in situ during the load rejection at 100%WG opening are shown in Figure 1. Different behaviours are observed for the parameter interaction before and after the complete closure of the WG (marked with the vertical magenta line) corresponding to 20 seconds in this case. A mutual influence interaction between the time evolution of the spiral casing pressure (upstream pressure with red color in Fig. 1) and the draft tube pressure (downstream pressure with blue color in Fig. 1) is observed during the reduction of the turbine volumetric flowrate until the complete closure of the WG at t=20 seconds [5]. As expected, this interaction is no longer identified after closing the WG because the two parts of the pathway (upstream and downstream of the WG) are completely separated.

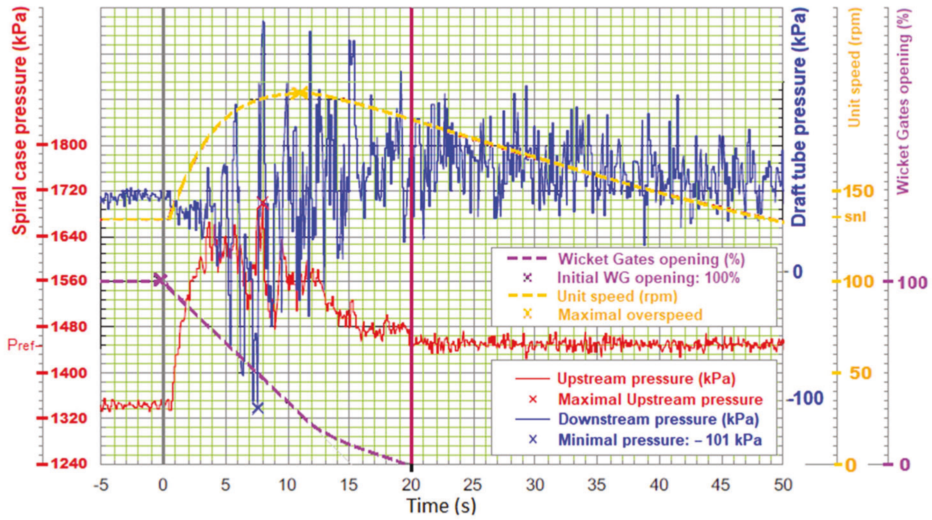

Figure 1. Time evolution of Francis turbine key parameters measured in situ during a load rejection from 100 %WG.

The interaction observed before the complete closure of the WG is analyzed further. This interaction suggests that the phenomena developed in the draft tube influence the behaviour upstream to WG. The time evolution of the left side graph over time for the upstream/downstream parameters under the influence of the interaction established by the flow passing through the turbine is shown in Figure 2. The scales of representations are different: on the left the spiral case relative pressure (MAWP = 1820 kPa, Pref = 1442 kPa) and on the right the absolute downstream pressure.

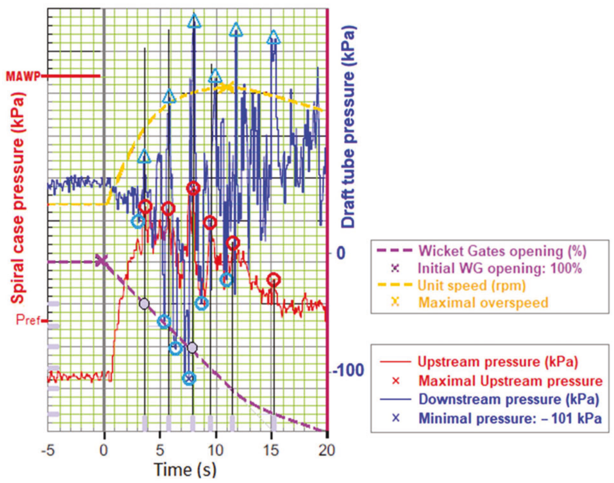

Figure 2. Detailed view of temporal interaction between upstream and downstream pressure signals recorded in situ during load rejection procedure from 100 %WG.

Regarding the evolution on the presented graphs, for the pressure in the spiral chamber (red graph) as well for the downstream pressure (blue graph) it can be observed that: (*i*) overpressure peaks (identified by red circles) occur at 3.7, 5.8, 8.0, 9.5 and 11.5 seconds so with an approximate periodicity of 2.0 seconds, for 75, 62, 50, 37 and 25 %WG; (*ii*) the evolution trend of the overpressure peaks (the envelope of the maximum values identified by red circles) is correlated with the turbine overspeed (yellow dash-line curve); (*iii*) moreover, the maximum overpressure peaks follow a sharp increase of the unit rotational speed (between 0 and 8.0 seconds); (*iv*) the draft tube pressure peaks (identified by blue triangles) are almost simultaneous with the overpressures in the spiral chamber, even seem to precede them; (*v*) minimum vacuum values in the draft tube (identified by blue circles) always precede overpressures in the spiral casing by approximately 0.5 seconds; (*vi*) the lowest depression in the draft tube (x and blue circle) precedes the highest overpressure in the spiral chamber (x and red circle) at time 8.0 seconds for 50%WG.

The study revealed a temporal interaction between pressure signals recorded in situ that induce water hammer. From previous observations, it can be underlined that the turbine in overspeed influences the water flow by introducing a local hydraulic loss which varies with the value of the rotational speed. Due to the runner restriction, the average field pressure in the spiral case increases significantly in the first 3 seconds after load rejection, even though WG have just started to close (their effect is not yet maximal).

3. Analytical approach

An analytical calculation was done based on a model elaborated for the HPP. Certain simplifying assumptions were made: a linear decrease of the discharge during the WG closure, the friction effect was neglected and transient phenomena (cavitation, separation of the water column) were not taken into account. To verify the applicability of the overpressure formulas, the closing time tBAF was compared to the pipeline period $T = 2L/a$, where L = 198 m is the penstock length and a = 962.94 m/sec is the speed of acoustic water hammer wave [6]. This results in tBAF = 15 sec >> T = 0.4 sec, so we are in the "slow or gradual closure" case. For this domain, the Warren M.M. formula is used to calculate the peak overpressure as the second term in equation (1) for the total overpressure value [6]:

$$P_{MAX} = \rho\, g\, H + \rho \frac{\mathrm{L}}{t_{BAF}} V_0 \qquad (1)$$

where V_0 is the initial bulk speed of the water column before load rejection (t=0 in fig 1), g is the gravitational acceleration, H is the turbine head and ρ is the water density.

The analytical pressure values obtained with (1) are shown in Table 2:

Table 2. Maximum analytical pressure values during load rejection.

WG opening (%)	Effective closing time corresponding to %WG (sec)	Initial bulk velocity for the %WG (m/sec)	Maximum analytical pressure value (kPa)
100	15.00	10.16	1576
75	11.25	8.37	1590
50	7.50	5.12	1577
25	3.25	1.87	1553

4. Numerical investigations

The simulation software „*ALLIEVI*” [8] is applied to the HPP selected in our study. The maximum overpressure obtained with „*ALLIEVI*” software is validated against experimental data [7].

The numerical results for pressures time evolution within the spiral case (blue) and the draft tube (green) are presented in Figure 3. The simulation results show pressure variations with multiple peaks comparable to those obtained experimentally, see Figure 1. However, the general trend of the temporal evolution of the average pressure in the spiral case obtained by numerical simulation (omitting the pressure peaks) is slightly different, presenting a drop in pressure at the start of the WG closure (during the first 3 seconds).

The maximal water hammer overpressure values predicted are: 1697 / 1716 / 1657 / 1555 kPa [173 / 175 / 169 / 158 mwc] for 100, 75, 50 and 25 %WG.

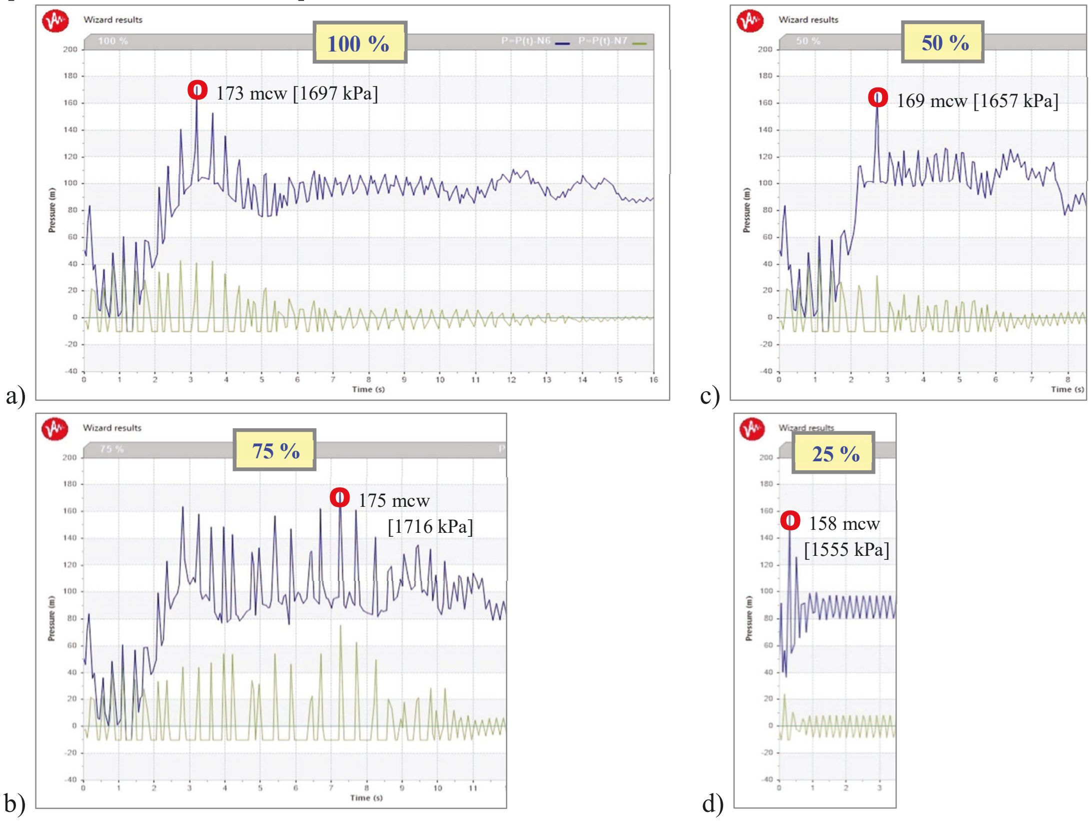

Figure 3. Numerical results obtained for pressure time evolution within the spiral case (blue) and the draft tube (green) during load rejection for effective closing time for each % WG of Francis turbine: a) 100 % WG, b) 75 % WG, c) 50 % WG and d)25%WG.

5. Validation of analytical values and numerical results against experimental data

For the evolution of the overpressure during load rejection on a Francis turbine, Figure 4 shows on the same graph the calculated analytical values (magenta line) and the numerical simulation result (blue line) compared against the experimental data (red line).

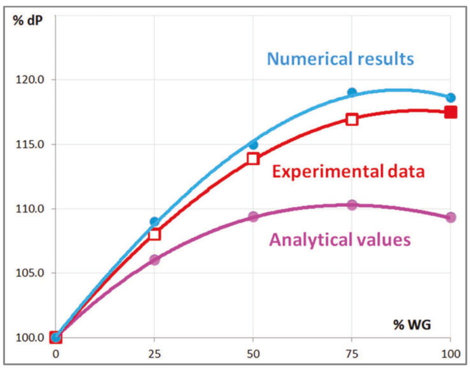

Figure 4 - Comparison of analytical values and numerical results against experimental data during load rejection for a Francis turbine.

It can be noted that: (1) the evolution of the analytical values shows an evolution similar to the experimental data, but with underestimated values; (2) numerical results reveal a similar trend to in situ measurements, with results exceeding experimental data as well as analytical values.

6. Conclusions

A methodology based on the conjoint analysis of water hammer factors is proposed to estimate the behaviour for a HPG unit during emergency shutdown / load rejection. On the basis of experimental data, analytical values and numerical results, the study on a Francis turbine highlights that the pressure oscillation downstream of the turbine influences the upstream overpressures.

Regarding the temporal interaction, some particular insights emerged from the current study: (*i*) other factors (e.g. runner in overspeed, draft tube turbulence) than the flowrate throttling by the WG impact as well on the overpressures; (*ii*) a pulsating phenomenon appears in the hydraulic passage during the load rejection as result of the pressure variation induced by the shaft torque fluctuation [7] obviously combined with water hammer wave reflections; (*iii*) downstream flow instability influences the upstream overpressures; *(iv)* the times when the overpressure peaks occur inside the spiral casing are related to the pressure and vacuum peaks in the draft tube and the sudden increase in the rotational speed; (*v*) the temporal interaction seems to diminish as the WG closes and the turbine flowrate decreases. In order to refine the performance of simulation results, it is preferable to identify suitable numerical software, capable of better matching the general evolution of the pressure (average value) in the spiral case, as well in the draft tube, with the measured values.

Regarding the amplitude of the pressure variation it is noticed that: (i) the analytical values underestimate the maximum experimental data by about 7%; (ii) the numerical results overestimate the maximum experimental data in limit of 2%; (iii) the evolution of overpressures follows the variation trend of the turbine overspeed; (iv) the worst behaviour occurs during transient zones (usually between 80÷60 %WG) most probably because of the hydrodynamic phenomena (e.g. vortex rope developed in the draft tube cone).

According to the correlation observed between the evolution of the overpressure and the runner speed, we assume that one of the main parameters which influence the evolution of the pressures in the HYP during the load rejection is the turbine in overspeed. In order to conclude, additional tests, as well as Fourier analyses, shall be carried out to focus on the phenomenology of pressure peaks.

It is planned for future research, that the impact of different technical solutions (e.g. air injection, add a second closing slope, multiple slopes closing law, modulate or non-linear closing law, asynchronous closing of the different wicket gates) on key parameters will be studied [9].

7. Acknowledgements

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