Challenges of meeting governor response requirements of hydro generating units within primary grid frequency control per Commission Regulation (EU) 2016/631

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European Commission Regulation (EU) 2016/631 requires participation of all new and upgraded units in primary grid frequency control (PFC). It is going to step into place on April 2019 in all EU countries. As a result in 2015 a working group was established in Slovenia, comprised of the legislation authority, HPP operators and equipment suppliers, with a main goal to define national acceptance criteria and acceptance test procedures for hydro generating unit governor responses.

Slovenian hydro turbine supplier Litostroj Power actively participated in this working group. Litostroj Power updated the turbine governor with new functionality to meet the primary frequency control requirements and prepared in-built testing modes to enable performing the governor acceptance tests.

This paper summarizes experiences of meeting primary control requirements during upgrading of governing systems on 26 Slovenian hydropower units on Drava and Sava rivers and highlights particular hydraulic system responses and limitations, possible solutions and technical explanation for the authorities. Discussion will be supported with measurements at recently commissioned Brežice HPP on Sava river.

1. regulation (EU) 2016/631 Requirements

Primary frequency control (PFC) is part of the grid frequency stability scheme (Figure 1) which was established by the "Union for the Coordination of the Transmission of Electricity" (UCTE) [1]. The objective of primary frequency control is to maintain a balance between generation and consumption (demand) within the grid synchronous area. By the joint action of all interconnected parties (Transmission System Operators / TSOs), primary control aims at the operational reliability of the power system of the synchronous area and stabilises the system frequency at a stationary value after a disturbance or incident in the time-frame of seconds, but without restoring the system frequency and the power exchanges to their reference values.

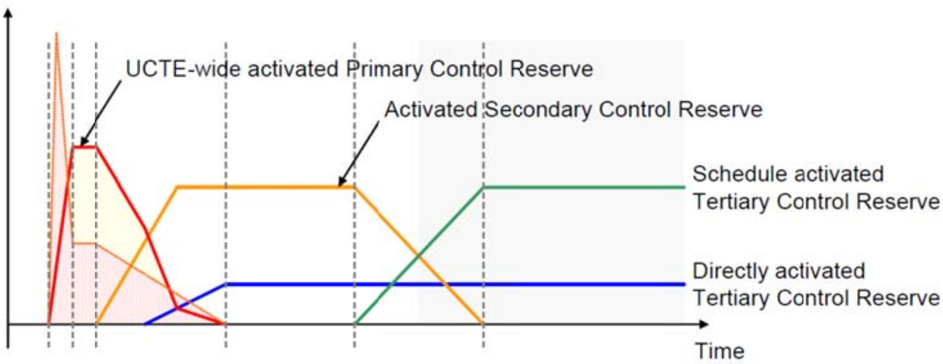

Figure 1 – UCTE Stability Scheme

In 2009 the UCTE becomes part of the ENTSO-E [2], the European Network of Transmission System Operators which now represents 42 electricity transmission system operators (TSOs) from 35 countries across Europe, thus extending beyond EU borders.

ENTSO-E was established and given legal mandates by the EU's Third Package for the Internal Energy Market in 2009, which aims at further liberalising the gas and electricity markets in the EU.

The European **Commission Regulation (EU) 2016/631** requires participation of all new and upgraded units in primary grid frequency control. European regulation is to step into place at April 2019, and the regulation is being transferred into the national legislations over the European Union. *Existing power plants are not part of the EU Regulation.*

1.1. Active power reserve activation rules

The ratio that links the required active power reserve activation with actual frequency deviation is called frequency droop – see eq. (1). Usual droop setting ranges between 4 and 5 for hydro power plants [3].

$$S1 = \frac{{-\Delta f}/{f_n}}{{\Delta P_G}/{P_{Gn}}} \qquad \text{eq. (1)}$$

Using the eq. (1), the active power reserve can be deducted as:

$$P_{ref} = -\frac{\Delta f^{[\%]}}{s_1} P_{max} \qquad \text{eq. (2)}$$

in which $\Delta f^{[\%]}$ is percent grid frequency deviation from its nominal value and s_1 the frequency droop set in the governor.

However, the droop ratio is not the only setting that needs to be taken into account in the governor. The UCTE Operation Handbook [1] that is now part of the commission regulation classifies “Generating Unit Types”. The governor response for smaller HPP units, classified under Type B units, only require the power reserve activation in case of grid frequency drop below certain value (LFSM-U: ‘limited frequency sensitive mode – underfrequency’; Figure 2). Larger units, classified under type C and D are normally required to act proportionally on any frequency deviation above ±20 mHz, while governor reaction is required up to maximum of ±200 mHz frequency deviation as shown in Figure 3.

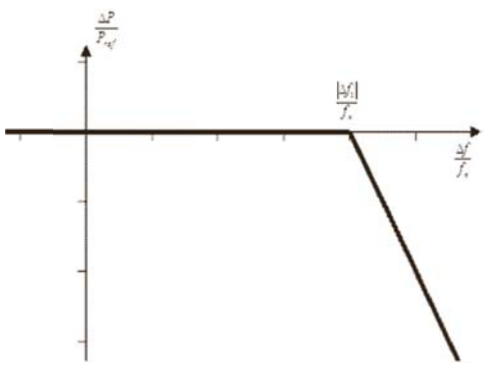

Figure 2 – Active Power frequency response capability for Generating Units Type B

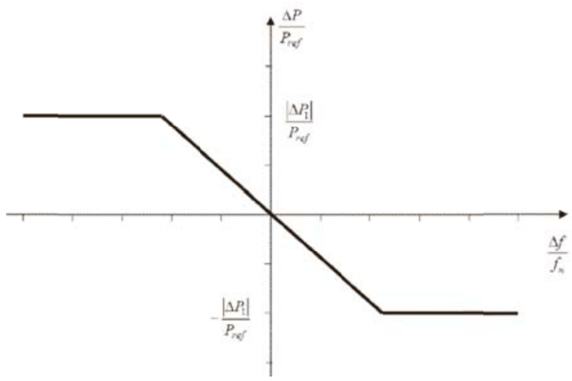

Figure 3 – Normal Active Power frequency response capability for Generating Units Type C and D

Unit types C and D must be also capable of operation under LFSM (‘limited frequency sensitive mode’) under- and over-frequency modes if so required by local Transmission System Operators.

The governor response and capacity thresholds, given in Table 1, varies among different grid synchronous areas. Type C units in Central Europe synchronous area have the capacity above 50 MW while in Nordic synchronous area the Type C units are classified already those above 10 MW.

Table 1 - UCTE Limits for thresholds for type B, C and D power-generating modules [4]

Synchronous areas	Limit for maximum capacity threshold from which a power-generating module is of type B	Limit for maximum capacity threshold from which a power-generating module is of type C	Limit for maximum capacity threshold from which a power-generating module is of type D
Continental Europe	1 MW	50 MW	75 MW
Great Britain	1 MW	50 MW	75 MW
Nordic	1,5 MW	10 MW	30 MW
Ireland and Northern Ireland	0,1 MW	5 MW	10 MW
Baltic	0,5 MW	10 MW	15 MW

Local legislation is to follow the EU commission requirements, however it may vary in certain details in terms of more strict requirements. In Slovenia for example, "SONPO" [3], a local code that determines unit behaviour within participation in primary frequency control, requires for all HPP units to respond according to expected response as for type C and D units. It means that even smaller capacity units above 1 MW should respond proportionally to any frequency deviation from stationary value.

Based on the governor droop settings and actual frequency deviation the required Power reserve is to be achieved within the activation parameters (see Figure 4). Initial delay on power activation should be below 2 s while full power reserve is to be achieved in a linear way within the 30 s time frame.

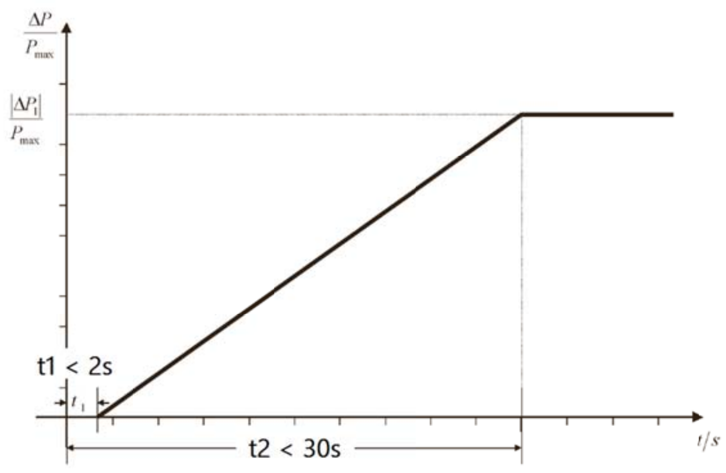

Figure 4 – Parameters for activation of active power

1.2. Actual frequency deviation in grid synchronous areas

Actual frequency deviation conditions are indeed not favourable for generating units that take part in the primary frequency control scheme. Measured fluctuation in different synchronous areas shows continuous grid frequency fluctuations outside the accepted dead-band range of ±20 mHz that represents the sum of the accuracy of the local frequency measurement and the insensitivity of the controller (governor).

Frequency fluctuations in Central Europe synchronous area (measured in Slovenia in 2017) as seen in Figure 5 fluctuates approximately on the minute basis with amplitudes up to and in certain occasions above 30 mHz peak-to-peak.

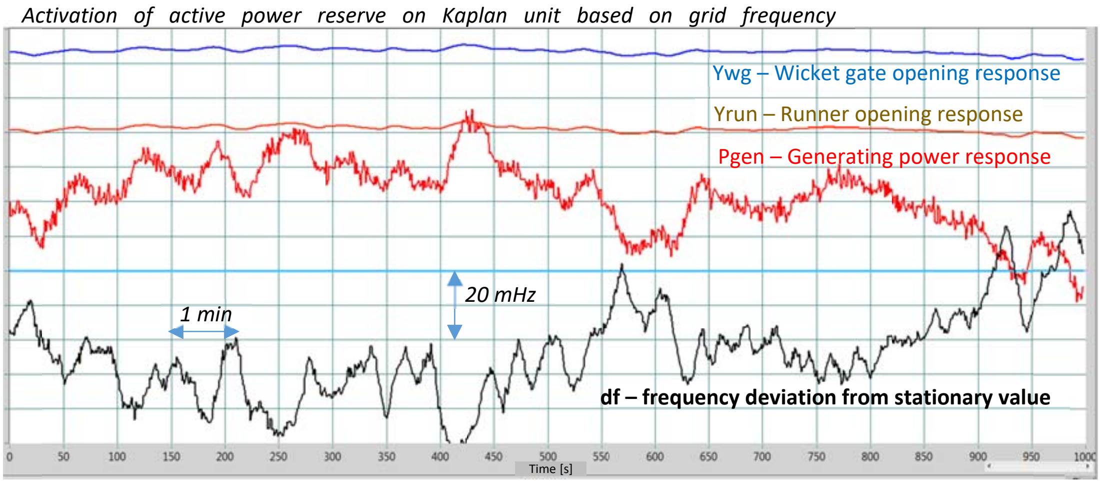

Figure 5 – Actual unfiltered frequency fluctuation in Central Europe synchronous area; August 2017

In Nordic countries (measured in Finland in 2017), the frequency fluctuation conditions are even worse, showing the fluctuation period of approximately 1.5 min and amplitudes up and occasionally above 100 mHz peak-to-peak.

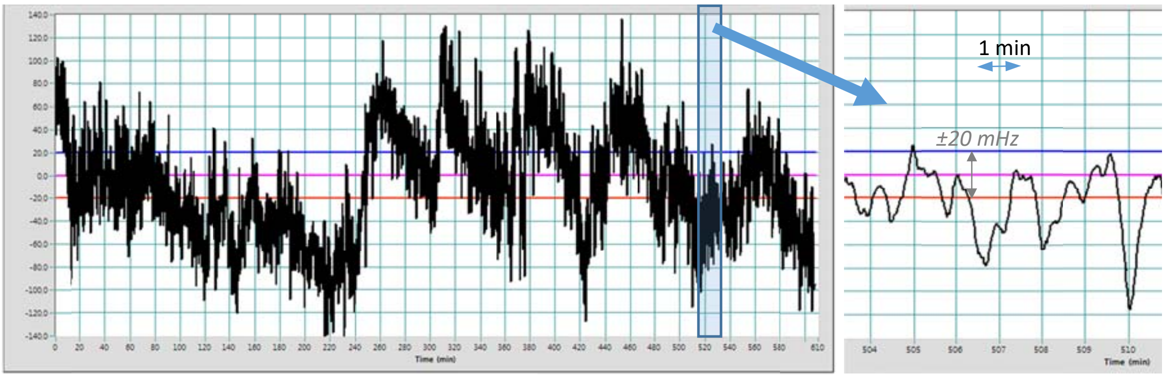

Figure 6 – Actual frequency fluctuation in Nordic synchronous area; 10 hours recording, August 2017

In both cases, when frequency conditions analysed, it can be seen that there are frequency fluctuations present in the grid system approximately with 1 minute cycles. Activation of power reserve within PFC and thus governor action is therefore required on the minute basis. Based on the actual grid frequency fluctuation, Figure 5 shows the required power reserve activation and the governor response for the Kaplan unit governor where no “sleeping runner regulation” [5] is applied.

2. Litostroj Power’s governor type DTR-03

In 2015 a working group comprised of the legislation authority, HPP operators and equipment suppliers was established in Slovenia with a main goal to define acceptance criteria and acceptance test procedures for hydro generating unit governor responses. Based on the workgroup work a code was published [6] specifying acceptance tests to be conducted by the authority for all units that are to take part in frequency primary control.

Litostroj Power governor type DTR-03 was developed for the speed-governing of the Kaplan type turbines. The main objective of the digital governor programing update in 2017 was to meet the requirements regarding the required governor response as per the EU commission [4] as well as local Slovenian legislation [6] [3] and to prepare in-built testing modes to enable performance of the required governor acceptance tests.

2.1. New functionalities for activation of PFC power reserve

The main challenge for the governor was to induce power output correction within the 2 seconds after the frequency deviation occurrence even for small frequency deviations such as 20 mHz. Standard PID control that enables stable operation in Power of Discharge regulation loop does not support the on-time activation of the power reserve for small frequency deviations that yield only small gate opening responses. Therefore, advanced governing functions needed to be introduced to assure these required functionalities by the commission:

1. To support the governor response within 2 seconds when power reserve activation due to frequency fluctuation is required.
2. To provide the required power reserve within the 30s time frame.
3. To assure linear power change rate for the Kaplan unit type governors.

2.2. Testing ready modes

The DTR-03 governors are equipped with various testing modes, all to support and expedite adjustments and governing parameter settings and the testing during commissioning. Since all new governors are to be tested and certified by the authorities for PFC, special testing modes and functionality was previewed to support such testing as well.

The implemented governor testing functions as a support for PFC governor response testing are:

- Provision for input (forced) frequency simulation signal.
- Governor simulation of the frequency deviation as a step and ramp signals.
- Automatic procedures for frequency deviation change as a support for hysteresis and other parameter testing.

2.3. Governor upgrades to mitigate Kaplan runner damages

Primary frequency control (PFC) is considered one of the generating equipment “Flexible operation” regimes. Flexible operation is considered to be anything that is not baseload operation [7]. Flexible operations such as frequency control might jeopardise Kaplan turbine’s internal blade mechanism to suffer increased fatigue, wear and damage. These facts have been confirmed by extensive investigation report [8] from Electric Power Research Institute (EPRI, USA) that summarizes the current knowledge related to the accelerated degradation of hydroelectric turbines and generators due to flexible operation.

Kaplan runners are considered to be critical unit mechanisms, as it is extremely hard to access the vital parts and practically impossible to perform any inspections during the lifetime without extensive dismantling works and unit outages. Due to the influences of other renewable power sources on the grid frequency (such as wind and solar), hydro units of Kaplan type that participate in PFC suffer from constant need to react on the grid conditions. The governor is required to adopt power corrections practically on the minute basis. Number of runner movements and thus induced load cycles in such operation is dramatically increased comparing the stationary operation with constant governing references. Increased number of load cycles in runner mechanisms affects the steel structure, bearings and seals. In quite a few cases, we have seen the customers were not aware of loading collectives due to participation in PFC. Anticipated effects of flexible operation on turbines and related components originate from grid PFC conditions that are causing a significant increased number of small regulating angles in the wicket gate mechanism [9]. Consequently, small regulating angles in runner mechanism are present as per Kaplan unit’s cam relationship as well.

For the PFC, Litostroj Power developed and recently enhanced advanced “sleeping runner function” [5] to minimize required runner movements due to grid frequency fluctuations and to support runner preservation in such operation. The algorithm takes into account the maximum efficiency drop due to “slight” unit off-cam operation as well as avoiding any risk for runner blades cavitation. It has been shown that from expected 120 moves per hour (2 × No. of cycles following the grid frequency fluctuation as in Figure 5 and Figure 6), the stabilizing algorithm reduced the required moves down to 20-30 moves per hour. However due to the requirements for achieving the power reserve (see chapter 1.1), the allowed runner operation dead band vary over the unit operating range. In this regard, the life expectancy benefit for using advanced PFC governing functions is considered to be in range 2÷4 compared to traditional governors. Expected averaged unit operation efficiency drop is maintained below 0.5 % which in comparison with the risk of runner failure is an acceptable price to pay.

Litostroj Power is also applying several other approaches toward mitigating the Kaplan runner mechanism fatigue issues due to unit participation with PFC. New governing requirements and expected increased load cycling showed to be an important aspect to be considered during the Kaplan runner mechanism design [10]. *For older units, remaining lifetime assessment under PFC is offered to determine if runner mechanism is to be upgraded before the PFC is applied within acceptable risk for operation.*

2.4. Statistical operation monitoring

New statistical and governor data gathering module was also developed to follow all kind of occurrences such as number of starts, stops, load rejections and trips, time spent in different loads and operating regimes. Such packed information is able to be followed and kept within the governor without the support of external monitoring systems. On the other hand, gathered data offers insight into the way the unit is operating and offers possibility to compare and observe changes in a way the units are operating over the years.

Importance of the gathered data expressed in cases when existing equipment remaining lifetime assessment is to be performed and the cases when equipment refurbishments are planned. The governor statistical module was designed to offer all the data necessary for future fatigue related analysis and arisen issues solving. When this data are supported with high precision commissioning measurements remaining lifetime assessment tends to be simple and reliable.

3. Experiences with upgrading of governors

In 2017 and 2018, Litostroj Power upgraded 26 governors on double-regulated Kaplan and Bulb units on Drava and Sava river cascades as well as installed 3 new governors with same functionality on a new HPP project.

All upgraded governors were digital turbine governors, some already dating back in the year 1999 therefore the objective of the upgrade was not only update to meet the PFC requirements but also to upgrade and in some part to change the existing digital equipment to the latest versions. However, one of the most important upgrades in terms of PFC was replacement and upgrade of grid frequency measurement module with the equipment which allowed the measurement with minimum uncertainty.

Most of the governor upgraded projects falls in the “low” net head range of 7 to 15 m (see Figure 7) with the exception of Zlatoličje HPP, which has the largest and most powerful Kaplan units installed in Slovenia. The later project has a long intake channel installed requiring very slow discharge changes in operation with restrictions in loading and unloading ramps, so the project itself is not representative in a sense of analysing the power delay in the governing response under PFC.

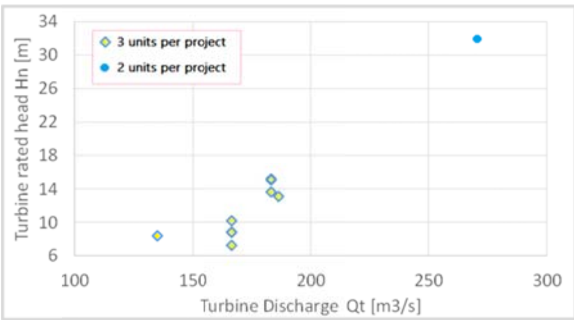

Figure 7 – Upgraded governor projects head and discharge ranges

On all the mentioned projects there are double regulated Kaplan or Bulb units installed for which the governors were successfully upgraded.

However we noticed strange system behaviour under PFC operation that was similar on all units. Once wicket gates movement was triggered to follow PFC, runner instantly follows as per installed cam relationship, while the power activation response lags and even goes for a while in opposite direction (Figure 10). It was realized that when WG are moved in closing (and similarly in opening) direction, small scale pressure surge is always present in the system, having few seconds of transient increase in the net head and consequently power increase. This phenomenon, which prevents instant power activation in desired direction, is seen either when the unit is loaded or unloaded disregarding the speed of operation. It was seen that with lower unit discharges such phenomenon diminishes and that the phenomenon has larger effect under operation with lower net heads comparing to high net heads.

The power activation response lagging phenomenon was measured both on old units with old mechanical governors as well as after upgrade to latest digital governors. In this study, the “power lagging” is considered any delay in the required power activation in desired direction. *If decrease of the power is required under PFC, than the* ***power activation response lagging*** *(or power lagging in this paper) is considered as a time between the occurrence of the frequency incident and the time that the active power begins decreasing below the stationary value present before the frequency incident – see Figure 10.*

3.1. Case study – Brežice HPP

Brežice HPP is a run-of-the-river hydropower plant on the Sava River (Figure 8). Each of the turbine piers contains a vertical Kaplan turbine and a generator above it –and cross-section in Figure 9. The power plant was commissioned in 2017. It is designed to operate between 9.6 and 14.3 m of available head and, with the net capacity up to 3 × 21.4 MW at the highest head.

During the authority PFC tests [6] the units of Brežice HPP were among the units that did not reach the 2 s power activation response time after the induced frequency incident.

Field tests have shown that during the movement of the guide and changing the flow through the turbine an imbalance occurs between the level of the upper water before the trash racks and the level acting on the turbine runner (spiral case pressure). Cause of this problem was at first attributed to water inertia in the form of water starting time (T_w), but this was excluded due to the fact that the value of T_w is of a much smaller size order. Clearance of the guide vane regulating mechanism was also checked since this can have an influence on the response (dead) time. Again, combined clearance at maximum possible value was of a much smaller size order.

Figure 8 – Brežice HPP

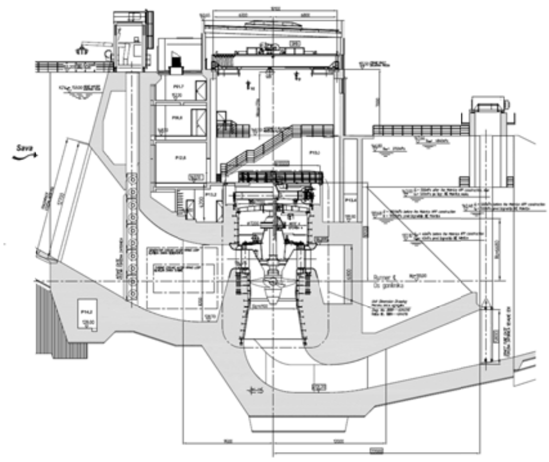

Figure 9 – Brežice HPP cross-section

It was expected that the cause of the problem is nor the mechanical side of the turbine nor the governor settings but a *hydraulic system feature* related to the changes of pressures at turbine inlet and outlet.

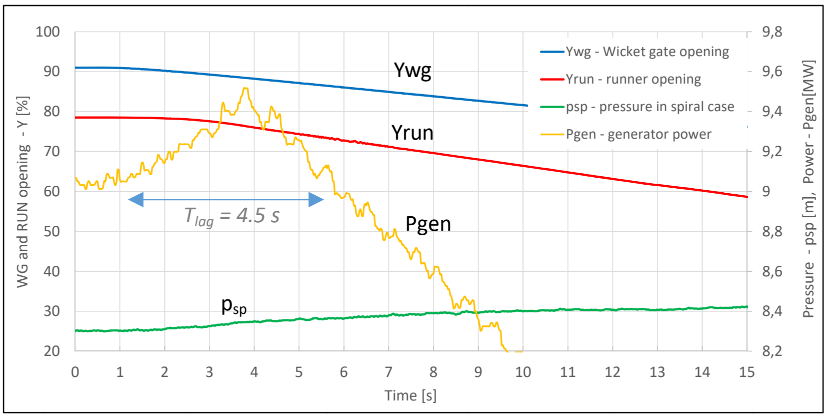

Figure 10 – Measured power output lagging phenomenon on Brežice HPP operating at 8.5 metres head and 90 % of WG opening [11]

We have decided to perform computer simulations to check the power response activation lagging as a hydraulic system feature. Brežice HPP project was a new unit installation which's governors already had to achieve the PFC requirements [12]. Since it was a new installation, a full scale transient simulation model was already prepared [13] and could be used for detailed simulations.

First simulations on high head (see Figure 11) showed similar response as seen during the measurements on lower heads (Figure 10). The extent of the phenomenon in simulation was of a smaller scale as measured, but without taking into account regulating system clearances it already exceeded the time requirement of 2 s in power response (Figure 11).

Due to the fact that head loses and thus related power response delay is related to the hydraulic system itself and the corresponding output power response delay cannot be avoided. This fact has been tested on site by applying different governor PID Gain settings. Higher the wicket gate opening response was applied, higher the transient pressure surge was induced and in all cases the power activation response lagged the gate opening.

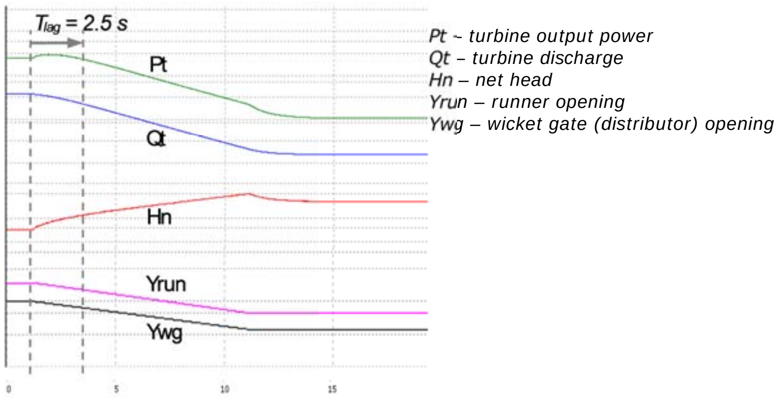

Figure 11 – Simulation of Power response for Brežice HPP operating at 80% discharge and high net head

Based on all above facts it was concluded that the power activation response delay in PFC is not a governor but powerplant's hydraulic system feature. In such cases the governor response is to be evaluated based on the gate response, which on our project showed to be well within 2s as required by the Code.

Additional simulations were performed to investigate the power lagging phenomenon in detail. When the 0.2 Hz frequency change incident is considered at 5 % speed droop setting in PFC, according to eq. (2), the 8% of output power is to be activated in 30 seconds. This gives us constant gate operating ramp of 375s. By the rule of thumb, the initial gate ramp should be faster to achieve the power response within the 2 s, meaning that 200 s ramp is a good basis for PFC Power lagging analysis.

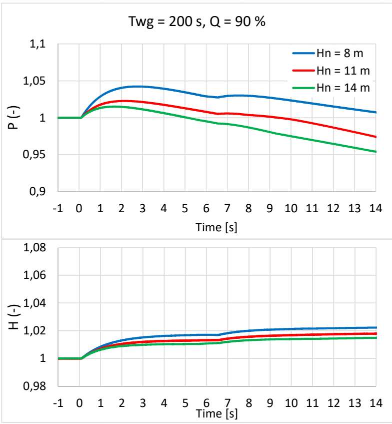

*Figure 12 – Influence of **net head variation** on the power lagging phenomenon; simulated for turbine discharge at 90% and closing ramp of 200 s*

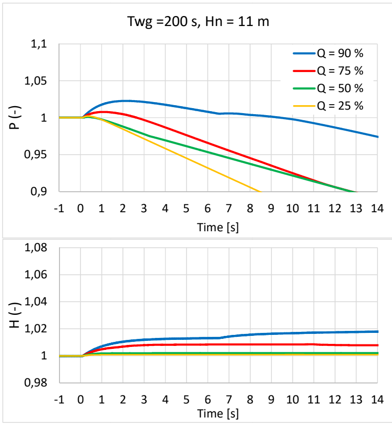

*Figure 13 – Influence of unit **discharge variation** on the power lagging phenomenon; simulated net head of 11 meters and closing ramp of 200 s*

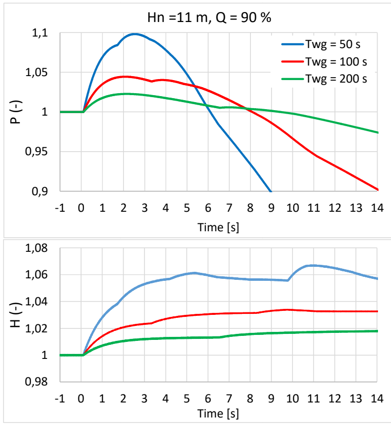

*Figure 14 – Influence of the **wicket gate closing ramps variation** on the power lagging phenomenon; simulated for turbine discharge at 90% and net head of 11 meters.*

The following conclusions can be made based on the measurements and simulations performed:

- Operation at small net heads yields longer power lagging times. This originates from the fact that the pressure surge is practically independent from the net head; however, per cent change of the head variation due to the pressure surge is manifested more on low operating heads. *At high operating heads it is expected that the power lagging time may even disappear.*
- Power lagging is only present at large unit discharges; it was neither seen during measurements or the simulations for low unit discharges. For Brežice HPP the limit was above 60 % of the rated discharge; however, the limit may vary for other power plants.
- Shorter (quicker) guide vanes closing ramps only influence the extent of pressure surge and power deviation; however, the influence on the power lagging is not significant and can be considered as uninfluential for practical use.

4. Conclusions

European Commission Regulation (EU) 2016/631 requires of all new hydro power plants to participate within the primary frequency control scheme. The required power reserve that is to be activated is to be achieved within 30 seconds time frame while power response is to be initiated already within the 2 seconds after the frequency incident occurs.

Achievement of the later requirement showed to be a problem for low head power plants. Unfortunately, hydro generating unit response is not limited only by the effectiveness of governor response adjustments, regulating devices and runner blade mechanisms but also by the intake hydraulic system characteristics. **Reservoir size, intake channels, trash racks, penstocks, etc., they all can influence the system response time.**

Such phenomenon have been observed on all 29 units during the governor upgrading and new installation works for Kaplan and Bulb units operating at heads below 15 meters. All the upgraded or newly installed governors successfully passed the authority testing with the exception in power activation lagging that exceeded the required 2 second response, for which an explanation had to be prepared. It was concluded that the power response delay in primary frequency control is not a governor but a hydraulic system feature.

Additionally, with inbuilt governing features the Litostroj Power speed governors with advanced Kaplan Runner features confirmed to be a good solution for mitigating the fatigue and wear related problems for unit participation within the primary frequency control.

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