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# Assessment of ancillary services contribution of a Kaplan turbine using different advanced technologies

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**Abstract.** With the decarbonization of the electric power networks, a massive integration of non-dispatchable Renewable Energy Sources drastically changes the grid balancing. Hydroelectric Power Plants already significantly support electricity power system flexibility with innovative solutions such as variable speed units, fast frequency control, fast generating to pumping modes transition, high ramping rate, inertia emulation, etc. However, the choice of technology is specific to the hydropower plant and requires in-depth studies to quantify the ancillary services contribution.

In the framework of XFLEX HYDRO H2020 European research project, 7 demonstrators were analysed and different technologies were compared to extend the ancillary services contribution. Among these demonstrators, one of the four Kaplan units of Vogelgrun Run-of-River (RoR) power plant has been selected to be hybridized with a small size battery. In this particular case, the Battery Energy Storage System (BESS) works in tandem with the hydro unit, thanks to a joint control algorithm, and optimizes the ancillary services contribution of the power plant. To assess the interest of this technology, a 1D SIMSEN model of this RoR power plant was created and validated with site-measurement. A particular attention was paid to the modelling of the existing turbine governor combining the control of the flow of the Rhine river and the frequency Containment Reserve (FCR).

This article presents a comparison of 3 different technologies applicable for this RoR power plant: i) fixed speed technology used as a reference case, ii) variable speed technology and iii) Hydro Battery Hybrid (HBH) technology. The methodology consists in extending the 1D SIMSEN simulation model to the different technologies and assess the different ancillary services contribution, such as the Frequency Containment Reserve (FCR), the Fast Frequency Response (FFR) and the black start capability. This analysis is a contribution to the so-called Ancillary Service Matrix (ASM) presenting the ability to deliver the different ancillary services combined with the applicable technologies. The results are available as a public deliverable of the XFLEX HYDRO H2020 European research project.

## 1. Introduction

On the way to the decarbonization of the electric power networks, a large increase of stochastic renewable energy production is expected to cause much higher volatility in the Europe electricity system [1]. Grid operators must constantly balance supply with demand to keep the system stable and the ancillary services are becoming significant assets for the different Hydro Power Plants.

In the framework of the XFLEX HYDRO H2020 European research project, the overarching objective is to develop and demonstrate new technological solutions capable of being integrated in different types of Hydro Power Plants (HPP) to improve its efficiency and performance with respect to the provision of several Electric Power Systems (EPS) services [2]. Among the 7 hydropower plants studied for this project, one of the Kaplan units of Vogelgrun Run-of-River (RoR) power plant has been selected to be hybridized with a small size battery. In this very particular case, Battery Energy Storage System (BESS) and hydro unit work in tandem, thanks to a joint control algorithm. The BESS provides small but frequent and fast power variation, whereas the hydro unit still contributes to Frequency Containment Reserve (FCR) when grid frequency variation is larger than what the battery can handle. The hybridisation with a BESS enables to reduce significantly the wear and tear of the guide vane and runner blade actuator mechanisms of the Kaplan turbine, while complying with the Grid Code specification for FCR, see [3].

In this paper, this Hydro-Battery-Hybrid solution was compared with the variable speed technology [4] [5] [6] [7] characterized by a Full Size Frequency Converter (FSFC) and the fixed speed used as a reference case. The methodology to assess the control performances of these technologies involves creating a 1D numerical model of the RoR power plant with the SIMSEN software and including the relevant control system for the fixed speed, the BESS and the variable speed technologies. These models include detailed representation of the hydropower plants 1D dynamic behaviour including water hammer phenomena in waterways, 2 quadrants quasi-static characteristics of the hydraulic machines and unit rotating inertia effects. After a selection of a relevant grid code for the different flexibility products, systematic 1D simulations of the different ancillary services were performed for each technology and the corresponding performances were quantified.

## 2. Modelling of the Vogelgrun power plant

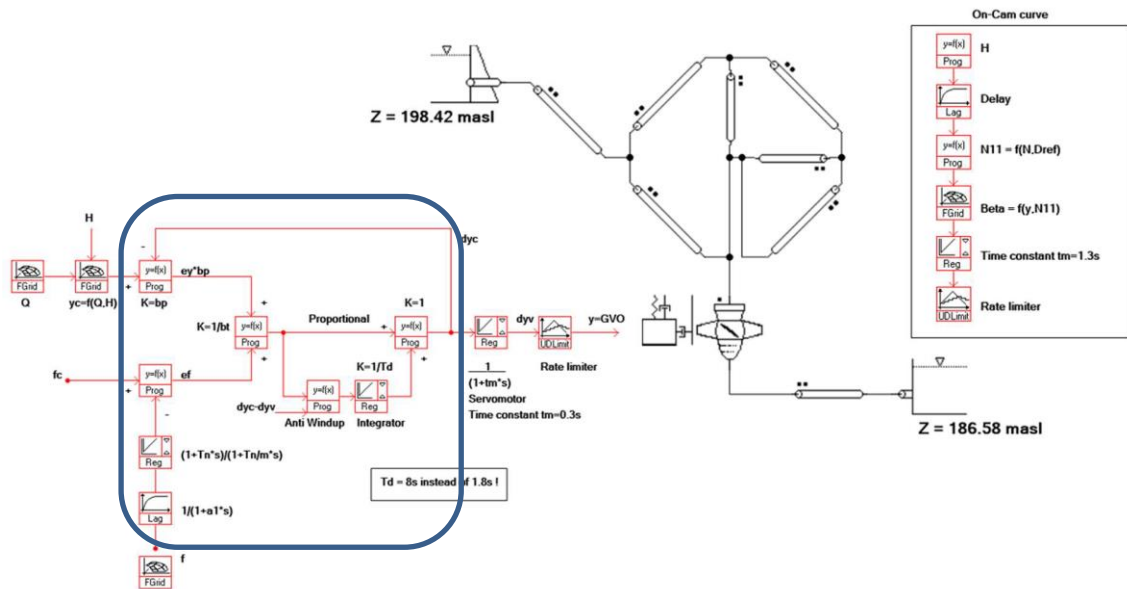
Vogelgrun demonstrator is a 140 MW Run-of-River (RoR) HPP, located in France on the “Grand Canal d’Alsace”, 80 km South of Strasbourg. The power plant features 4 units equipped with double regulating Kaplan turbines. The main hydraulic characteristics are presented in Table 1.

**Table 1.** Vogelgrun hydraulic features.

<b>Head</b>	
Minimum	9.0 mWC;
Rated	11.5 mWC;
Maximum	14.0 mWC
<b>Type of turbine</b>	Kaplan turbine
<b>Number of units:</b>	4 units
<b>Rated rotational speed</b>	83.3 min <sup>-1</sup>
<b>Rated mechanical power</b>	4 x 35 MW
<b>Rated power/storage of the BESS</b>	650 kVA / 370 kWh

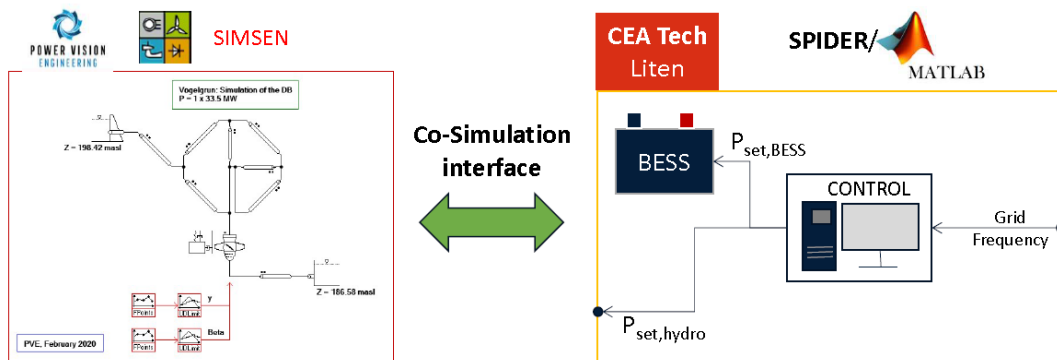
A 1D SIMSEN numerical simulation model of Vogelgrun HPP was developed including the water intake, the Kaplan turbine and the draft tube of the unit, see Figure 1. As the units are completely independent, only the unit G1 was modeled. A particular attention has been paid to the modeling of the spiral case in order to consider the evolution of the cross-section area and the distribution of the discharge, see [8]. The SIMSEN model also includes the turbine governor combining the control of the

flow of the Rhine river and the frequency primary control. The turbine governor is operated in guide vane position control mode and uses on-cam look-up table to define the blade pitch angle set point as function of the head and the guide vane position.



**Figure 1.** SIMSEN model of the Vogelgrun power plant.

For the modelling of the battery, the SIMSEN model was coupled to the simulation model of the BESS and its controller in the SPIDER/Matlab simulation platform developed by Commissariat à l’Energie Atomique et aux énergies alternatives (CEA) to enable the co-simulation of the hybrid unit using Functional Mockup Interface (FMI), see Figure 2. With the co-simulation, both simulation tools SIMSEN and SPIDER run in parallel and exchange predefined quantities at given exchange points in time. In particular, the power set point for the turbine governor comes from the BESS joint controller model in SPIDER, while the actual power produced by the turbine comes from SIMSEN. The co-simulation enabled to validate the joint control strategy and optimize the corresponding parameters.

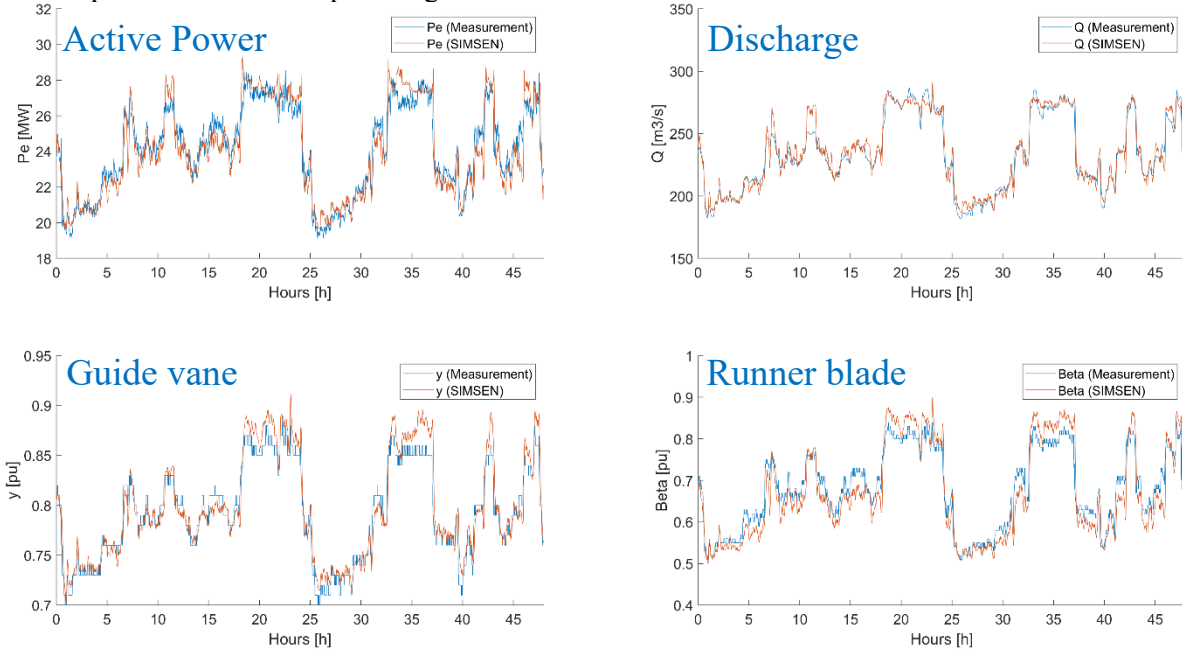


**Figure 2.** Illustration of the co-simulation interface between SIMSEN and SPIDER.

### 3. Validation of the SIMSEN model

The validation of the SIMSEN model was performed by comparing the numerical simulation results with the site measurements performed during August 1 and 2, 2019. By using turbine flow set point and grid frequency time histories, it was possible to reproduce the time evolution of the active power, guide

vane opening and blade angle with good agreement. Thus, the good reproduction of the active power validated the characteristic curve of the Kaplan turbine. Moreover, the good agreement for the guide vane opening confirmed the turbine governor model. Finally, the on-cam curve was also attested with the comparison of the blade pitch angle beta.



**Figure 3.** Comparison of the experimental measurement (blue line) performed during August 1 and 2, 2019 and the numerical results (red line).

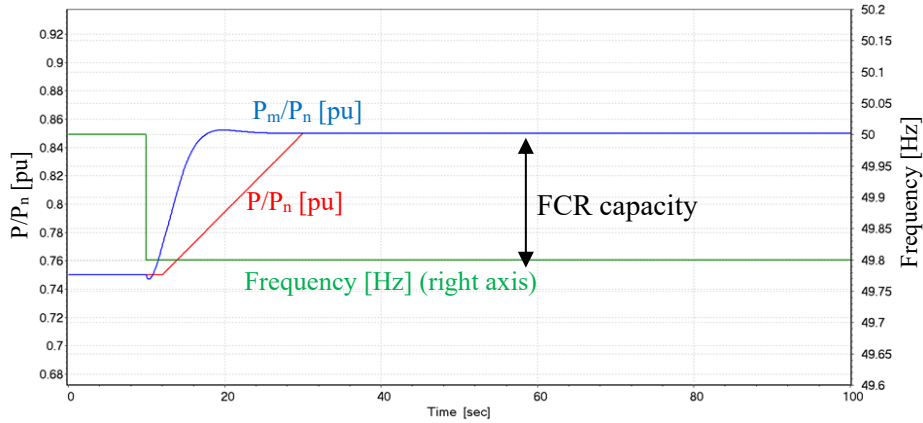
#### 4. Grid code selection

The assessment of the different flexibility products required the selection of relevant grid code or the definition of appropriate metrics when no grid code specifications were available. An overview of the ancillary services established by the European Commission Regulation was described by INESC TEC in the framework of the XFLEX HYDRO project [9] and the most appropriate grid codes were selected for each ancillary service.

##### 4.1. Frequency Containment Reserve (FCR)

This flexibility service also called frequency primary control aims to contain system frequency after the occurrence of an active power imbalance. The grid code of the French transmission system operator (RTE - Réseau de Transport d'Electricité) was selected to evaluate FCR service contribution [10]. Experimentally, the qualification test imposes a step frequency deviation from the nominal value of -200 mHz and +200 mHz to the turbine controller as input. In 30 seconds, the power response has to reach 100% of the primary control reserve. In Figure 4, an example of the power response is illustrated. The red line corresponds to the lower limit for the power, divided by the rated power  $P_n$ . The green line describes the frequency deviation on the right axis. The blue line is an example of mechanical power response  $P_m$  for a unit.

The operating conditions for this qualification test have been defined to ensure the most constraining conditions for the hydraulic power plant. For this load case, the water level in the upstream and downstream reservoirs are defined to obtain the minimum head for the unit in operation. The initial power set point of the unit is fixed to 75% of the maximal power. Finally, the other units are at standstill.

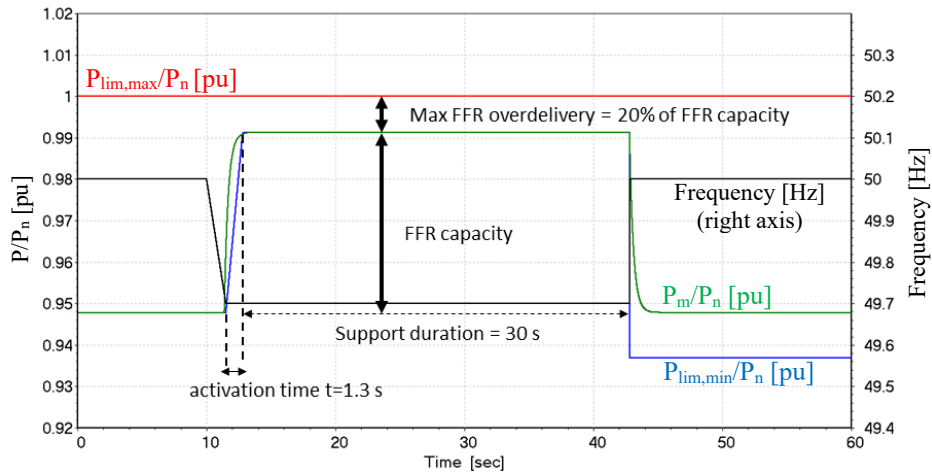


**Figure 4.** Example of a turbine power response after a frequency variation of -200 mHz.

#### 4.2. Fast Frequency Response (FFR)

This ancillary service is usually designed to provide an active power response faster than the frequency containment reserve service, which has a maximum delay of 2 seconds. The ENTSO-E document for Nordic Synchronous Area [11] was selected for FFR service quantification. The qualification test imposes a frequency drop and when frequency reaches the threshold of 49.7 Hz (-0.3 Hz), the unit must deliver the FFR power amplitude within a time of 1.3 s and has to maintain it during 30 s. Then, the frequency is restored to the rated frequency and the unit goes back to its initial power level.

In Figure 5, an example of the power response is illustrated. The red and blue lines correspond respectively to the upper limit and lower limit for the power. The green line describes an example of power response for a turbine in per unit. Finally, the black line is the frequency deviation on the right axis.



**Figure 5.** Example of power response for FFR with an activation time fixed to 1.3 s.

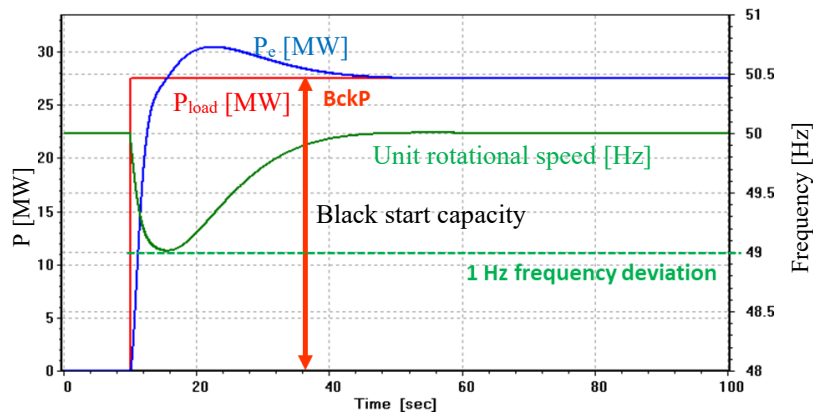
Finally, the operating conditions are defined to verify the qualification test under the most constraining conditions. Thus, the water level in the upstream and downstream reservoirs are defined to obtain the minimum head for the unit in operation. The initial power set point of the unit is fixed to  $P_{max}$ , minus 1.2 times the FFR capacity. The other units are at standstill.

### 4.3. Black start

The black start is the process of autonomous restarting operation of a power plant during a grid blackout, from a completely non-energized operating state and without any power feed from the network. While grid codes usually describe prerequisite to provide black-start service and specify that the unit must be stable in the case of isolated grid operation [10] [12], they do not describe how to carry out tests to quantify black-start performances.

For this qualification test, only the hydromechanical simulation model is considered, assuming purely resistive load connection leading to active power step changes. Assuming that voltage control is capable to maintain the network voltage constant, it corresponds to step of active power to a constant value and the maximum allowable unit rotational speed deviation is fixed to  $Df = 1$  Hz from 50 Hz in order to prevent load shedding activation. In Figure 6 the red line corresponds to the load activation and the blue line describes the variation of the active power. The unit rotational speed is illustrated with the green line on the right axis.

To obtain the worst operating conditions for this qualification test, the water level in the upstream and downstream reservoirs are defined to obtain the minimum head for the unit in operation. Moreover, the unit is stabilized at speed no load condition, *i.e.* at synchronous rotational speed in case of fixed speed technology and arbitrary rotational speed in case of variable speed technology. The value of the rotational speed before connecting electrical loads influences the black start capacity of the unit.



**Figure 6.** Example of power response for black start.

## 5. Assessment of the ancillary services contribution

Among the parameters of the PID controller, the unit G1 has the particularity to have an integration time  $T_i = 8$  s instead of 1.8 s which induces a slower response time than the other units. This modification was made in order to reduce vibrations between the different units. Nevertheless, the study of the ancillary services was carried out with an integration time equal to 1.8 s to get the best performance from the unit.

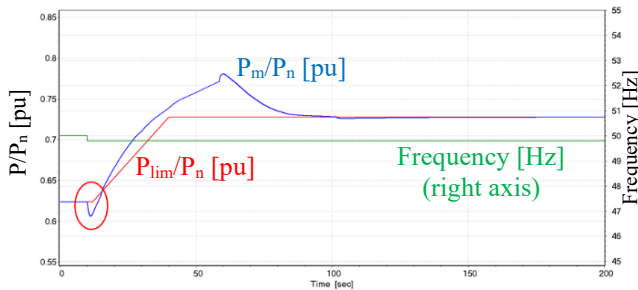
### 5.1. FCR

Currently, the 4 units contribute to Frequency Containment Reserve with a permanent droop  $B_s = 5$  %. For a frequency variation of -200 mHz, the mechanical power response  $P_m$  of the Kaplan turbine is faster, but not sufficient for the first few seconds, see Figure 7. Indeed, an adverse active power response occurs the first seconds after the grid frequency variation. This phenomenon is related to the non-minimum phase induced by the hydraulic system response and it cannot be reduced by changing the parameters of the PID controller. By analysing the transient behaviour on Figure 8, the guide vanes  $y$

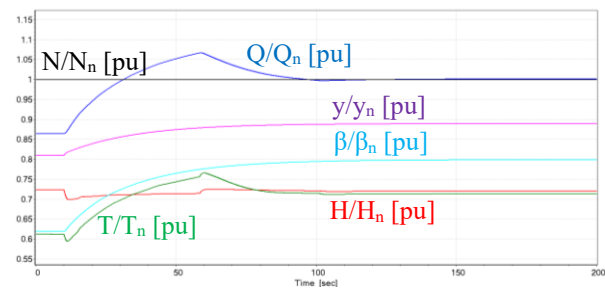
(pink line) and blades angles  $\beta$  (light blue line) do open to increase the active power, however the torque  $T$  (green line) decreases during the first seconds. The rotational speed  $N$ , the discharge  $Q$  and the head  $H$  of the unit are respectively the black line, the blue line and the red line.

To counteract this effect, the addition of a BESS will quickly provide the necessary power during the first few seconds, see Figure 9. The black curve indicates the power supplied by the battery on the right axis. Moreover, to fully meet the criteria for this ancillary service, the permanent droop was increased to 7.5 % instead of the initial 5 % for this operating point to ensure that the total power  $P_m + P_{BESS}$  is always above the power limit defined by the qualification test. Finally, thanks to the BESS, the FCR capacity is equal to 4.10 MW. The behaviour of the Kaplan unit can be seen in Figure 10.

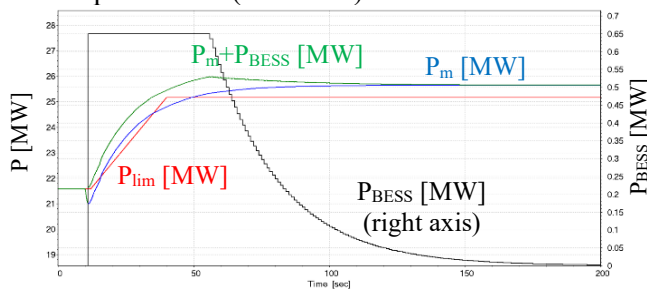
For the variable speed technology, the power response fulfils the qualification test with an initial permanent droop equal to 5 %, see Figure 11 and Figure 12. Thanks to this ability to follow the setpoint variation with small deviation, the permanent droop can be reduced to 1.7 % and the FCR capacity can be increased to 8.3 MW.



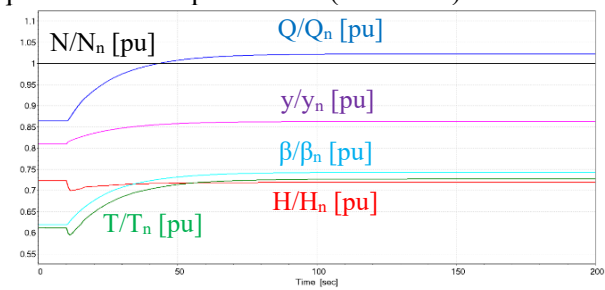
**Figure 7.** Power response without BESS for a frequency variation of -200 mHz with a permanent droop  $B_s = 5\%$  ( $T_i = 1.8$  s).



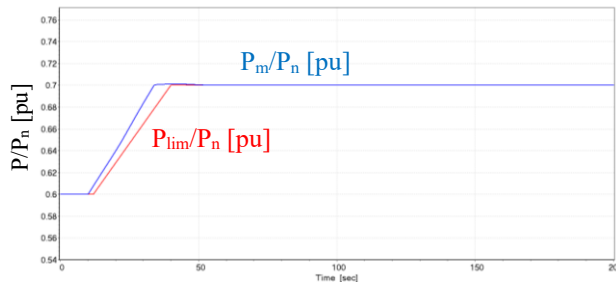
**Figure 8.** Transient behavior of the Kaplan turbine G1 for a frequency variation of -200 mHz with a permanent droop  $B_s = 5\%$  ( $T_i = 1.8$  s).



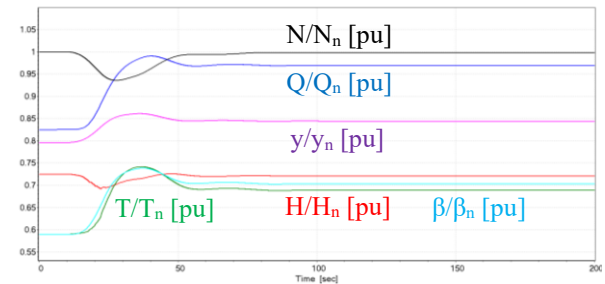
**Figure 9.** Power response with BESS for a frequency variation of -200 mHz with a permanent droop  $B_s = 7.5\%$  ( $T_i = 1.8$  s).



**Figure 10.** Transient behavior of the Kaplan turbine G1 with BESS for a frequency variation of -200 mHz with a permanent droop  $B_s = 7.5\%$  ( $T_i = 1.8$  s).



**Figure 11.** Power response with variable speed for a frequency variation of -200 mHz with a permanent droop  $B_s = 5\%$

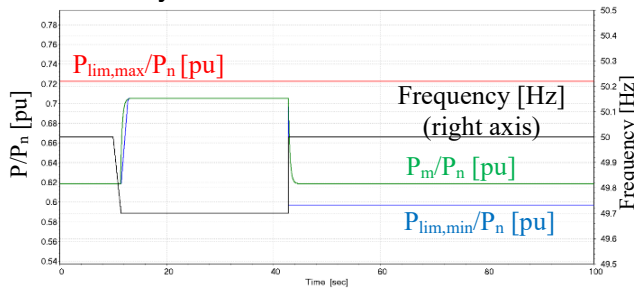


**Figure 12.** Transient behavior of the Kaplan turbine G1 with variable speed for a frequency variation of -200 mHz with a permanent droop  $B_s = 5\%$

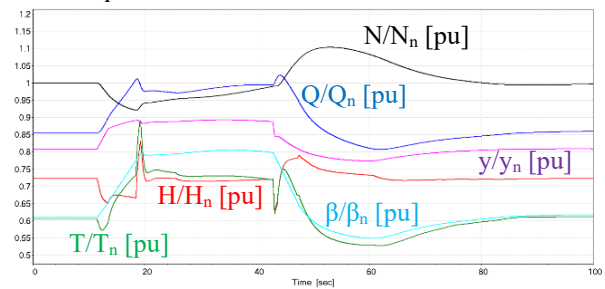


### 5.2. FFR

For this ancillary service, only the variable speed technology has a very fast dynamic response to be able to provide the requested power within the service timeframe. For the Kaplan turbine with the variable speed technology, the FFR capacity of 3 MW for the minimum head  $H_{min}$  is illustrated in Figure 13 and the transient behaviour of the unit is described in Figure 14. The BESS can also contribute to this ancillary service. Its contribution is limited to its nominal power of 0.65 MW.



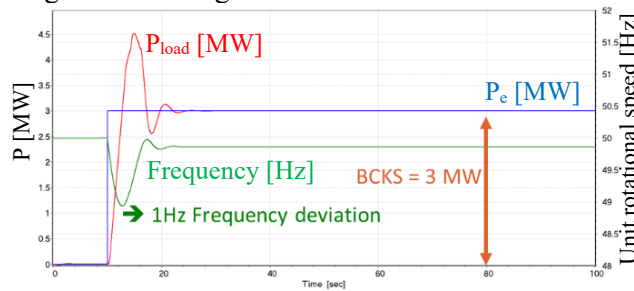
**Figure 13.** Output power response of the Kaplan turbine G1 activated at a frequency deviation level of 49.7 Hz.



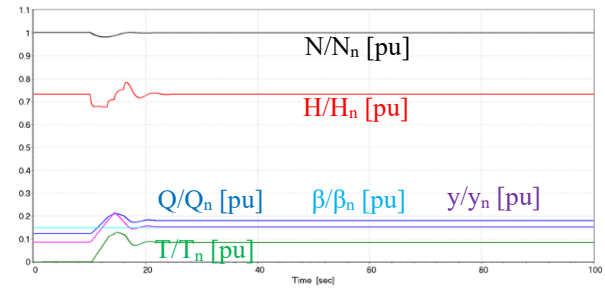
**Figure 14.** Transient behavior of the Kaplan turbine G1 activated at a frequency deviation level of 49.7 Hz.

### 5.3. Black-Start

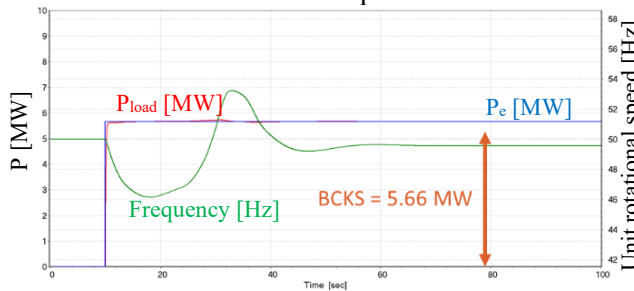
The aim of this simulation is to find the maximum electrical load which can be connected to the power network. For a minimum head, the maximum black-start capacity is 3 MW for the fixed speed. This capacity can be increased to 5.66 MW with the variable speed technology. The evolution of the unit rotational speed, as well as the variation of the active power are defined in Figure 15 and Figure 17 for fixed speed and variable speed, respectively. The transient behaviour of the Kaplan turbine is shown in Figure 16 and Figure 18.



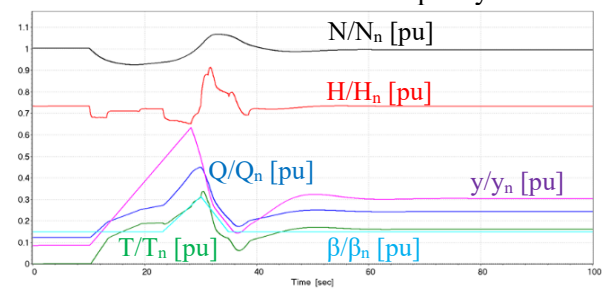
**Figure 15.** Fixed speed – black start in turbine mode - Maximum black-start capacity defined by a maximum unit rotational speed variation of 1 Hz.



**Figure 16.** Fixed speed – black start in turbine mode - Transient behavior of the Kaplan turbine G1 for the maximum black-start capacity.



**Figure 17.** Variable speed – black start in turbine mode - Maximum black-start capacity defined by a maximum unit rotational speed variation of 1 Hz.



**Figure 18.** Variable speed – black start in turbine mode - Transient behavior of the Kaplan turbine G1 for the maximum black-start capacity.

#### 5.4. Summary of the ancillary services contribution

By extending the 1D SIMSEN model to the different technologies, the ancillary services contribution of the Frequency Containment Reserve (FCR), the Fast Frequency Response (FFR) and the black start capability were assessed. Because of the adverse active power response, the qualification test of the FCR ancillary service cannot be fulfilled by the fixed speed technology whatever the value of the permanent droop  $B_s$ . To counteract this effect, the addition of a BESS will quickly provide the necessary power during the first few seconds. However, the permanent droop must be increased to 7.5 % instead of the initial 5 % to respect the criteria. With the variable speed technology, the adverse active power response is not a problem anymore and the permanent droop can be reduced to 1.7 %. Thanks to the quick power electronic response, the FCR capacity can be increased to 8.3 MW, instead of 4.10 MW for the BESS technology, see Figure 19.

The variable speed enables the FFR ancillary service, which is not adapted for the case of fixed speed as a very fast dynamic is necessary to be able to provide the requested power within the service timeframe. The FFR capacity is equal to 3.00 MW for the variable speed and to the rated power  $P_{\text{BESS}} = 0.65$  MW for the BESS. For a minimum head, the maximum black-start capacity is 3 MW for the fixed speed. This capacity can be increased to 5.66 MW with the variable speed technology.

		Fixed speed	BESS	Variable speed
FCR capacity	[MW]	NAN	4.10	8.30
FFR capacity	[MW]	NAN	0.65	3.00
Black start capacity	[MW]	3.00	3.65	5.66

**Figure 19.** Summary of the ancillary service contribution for each technology.

## 6. Conclusion

In this paper, three different technologies were assessed for different ancillary services contribution: the fixed speed technology used as a reference, the Battery Energy Storage System (BESS) and the variable speed technology. The methodology to assess the control performances of these technologies involves creating a 1D numerical model of the RoR power plant with the SIMSEN software and including the relevant control system. After a selection of a relevant grid code for the FCR, the FFR and the black start, systematic 1D simulations of the different ancillary services were performed for each technology and the corresponding performances were quantified.

For the Vogelgrun power plant, the quick power response of the variable speed technology enables bigger ancillary services contribution. The smaller capacity for the BESS is due to the small sizing of the battery but could be higher with bigger BESS. With the current sizing, the addition of the battery enables to fulfill the qualification test of the FCR service for the fixed speed unit. This hybridization enables also to reduce significantly the wear and tear of the guide vane and runner blade actuator mechanisms of the Kaplan turbine.

Finally, this analysis is a contribution to the so-called Ancillary Service Matrix (ASM) presenting the ability to deliver the different ancillary services combined with the applicable technologies. The results are available as a public deliverable of the XFLEX HYDRO H2020 European research project.

## Acknowledgments

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