Pushing the envelope of ancillary services with variable speed technology

M. Dreyer[1], C. Nicolet[1], S. Alligné[1], M. Seydoux[2], A. Jung[3], D. Cordeiro[4]
[1] Power Vision Engineering Sàrl, CH-1025 St-Sulpice, Switzerland
[2] EPFL PTMH, CH-1007 Lausanne, Switzerland
[3] Voith Hydro Holding GmbH & Co KG, 89522 Heidenheim, Germany
[4] EDP Gestão DA Produção De Energia SA, Lisboa, Portugal

email: matthieu.dreyer@powervision-eng.ch

Abstract. Hydropower is the backbone of energy transition thanks to its operational flexibility and ability to provide ancillary services. These grid support capabilities are called upon to play a major role to maintain the grid vulnerability at acceptable levels in view of the increasing penetration of stochastic and intermittent renewable energies. In this context, variable speed reversible pump-turbine technology is a key asset as it can extend the head operating range of a powerplant, enable power network control in pump mode and further increase the flexibility services to the electrical grid. Furthermore, by taking advantage of the so-called flywheel effect, variable speed enables the fast active power injection/absorption in pumping and generating mode. The additional degree of freedom offered by the variable speed opens the door to different control strategies for the hydroelectric plant, as the converter can be used for speed or power control. This can be exploited to maximize either the efficiency or the power reserve dedicated to grid support. In this paper, the strategies to maximize the ancillary service of Frades 2 pumped storage power plant (PSPP) are investigated. The plant features two high-head single-stage reversible variable speed units, coupled with 420 MVA doubly-fed induction motor-generators (DFIM). Using a 1D numerical model to simulate the power plant behavior, it is explored to which extent Frades 2 can deliver frequency containment reserve (FCR) power, while complying with the ENTSO grid code, and speed deviation constrains inherent to DFIM. By choosing a strategy which fully exploits the flywheel effect, it is established that the FCR power band can be equal to the whole operating range of the power plant. Moreover, the fast frequency response capacity (FFR) is also evaluated. It is found that by maximizing the energy stored in the rotating masses, each unit of Frades 2 can deliver up to 110 MW of active power in 1.3 seconds.

1. Introduction
Across Europe, countries are shifting from conventional fossil fuels for power generation to renewable energies such as solar and wind power. The growth of variable renewables is changing the way power grids operate, which can impact the stability and security of energy supply. By 2030, the EU aims for at least 32% of energy to come from renewable sources, and longer-term scenarios suggest an even more radical decarbonization of electricity by 2050. The hydropower sector will therefore be increasingly called upon to provide flexible and reliable energy services, capable of coping with variations in energy consumption and production. These so-called ancillary services help grid operators maintain a reliable electricity system, by addressing imbalances between supply and demand, and help the system recover after a power system event. In this context, the XFLEX HYDRO H2020 European Project intends to consolidate the control capacities of hydropower plants (HPPs) and showcasing how modern HPPs can provide the crucial power grid flexibility services required by demonstrating the potential of key hydropower technologies, see [1].
Among the technologies considered, the variable speed technology is a key asset for flexibility, as it enables to swiftly adapt the active power output of a unit. Indeed, the decoupling between the electrical and the mechanical systems of the unit is beneficial for the capability to provide faster responses with the appropriate control system as compared to synchronously connected units. In the basket of the

ancillary services being required by grid operators in European synchronous areas, this fast power injection or absorption ability is particularly well suited for the following services:

- **Frequency Containment Reserve (FCR)**: also known as primary frequency control, FCR aims to contain system frequency after the occurrence of an active power imbalance, by maintaining the balance between active power generation and demand within a synchronous area. For FCR providers in the Continental Europe (CE) Synchronous Area (SA), the service must be fully activated within 30 seconds and the power-generating module shall be capable of providing full active power-frequency response for a period between 15 to 30 minutes (specified by the Transmission System Operators (TSO) of each SA), see [2].
- **Fast Frequency Response (FFR):** FFR is usually designed to provide an active power response in the timeframe following inertial response (i.e., typically after 500 ms) and before the activation of the FCR. It is intended to further reduce frequency excursions after a disturbance and to increase the time that frequency takes to reach its lowest value. FFR service is a relatively new concept that may be required to sustain the dynamic frequency stability of the grid in face of increasing shares of variable renewables, see [2].

Furthermore, the control systems of variable speed units are also able to provide some **synthetic inertia**, which is an active power response proportional to the rate of change of frequency (RoCof) in the grid, with a response time much faster than FCR services. Since the rotational speed of variable speed units is disconnected from the power network frequency, the inertial response is emulated by a dedicated control loop in the variable speed controller to reproduce the inherent quasi-instantaneous power response of a synchronous machine to a frequency event, provided some energy buffer is available within the rotating masses. Inertia emulation control structure is based on the swing equation in order to achieve active power injection or absorption proportional to the RoCof [3-4]. However, no grid code nor metric are yet available for this particular ancillary service.

The additional degree of freedom offered by the decoupling between the electrical and the mechanical systems of the variable speed units opens the door to different control strategies for the hydraulic machine, as the converter can be used for speed or power control [5-11]. This can be exploited to maximize either the efficiency of the unit, or the power reserve dedicated to grid support. In this paper, it is explored to which extent Frades 2 pumped storage power plant (PSPP), which is a 780 MW plant with two variable speed units coupled with doubly-fed induction motor-generators (DFIM), can deliver FCR and FFR ancillary services, while complying with the ENTSO grid code and speed deviation constrains inherent to DFIM. To this end, the maximum contributions for the aforementioned services are quantified using 1D system simulation with the appropriate variable speed control structures.

2. Presentation of Frades2 PSPP

Frades 2 hydroelectric plant is a PSPP built between 2010 and 2017 on the Rabagão river in the north of Portugal. The plant is composed of two high head, variable speed units made of two reversible pump turbines, coupled with 420 MVA DFIM which are currently Europe largest and most powerful machines [1]. The main hydraulic and power generation characteristics are given in Table 1 [12]. The waterway includes a headrace tunnel, an upper surge tank followed by a sandtrap, a penstock that feeds the distributor of each unit, a lower surge tank and the tailrace tunnel, as shown on the left side of Figure 1. The pump-turbine, which is illustrated on the right side of Figure 1, is characterized by a specific speed of n_q=38 and a unit mechanical time constant of τ_m = 7.9 s.

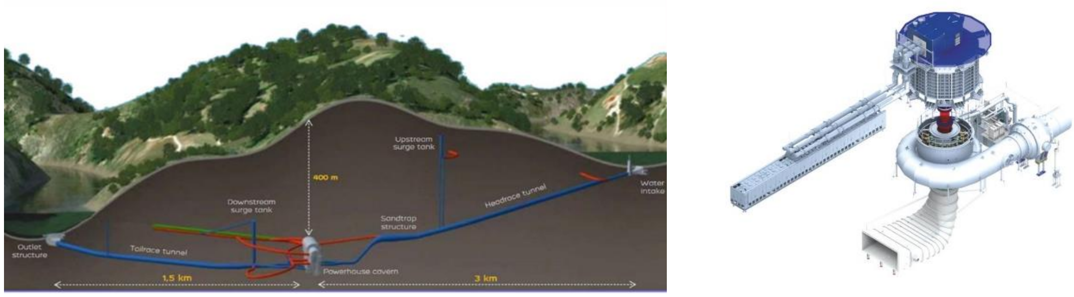

Figure 1 Left: Frades 2 pump storage power plant layout. Right: 3D view of the variable speed pump-turbine of Frades 2 PSPP.

Table 1. Frades 2 pump storage power plant characteristics

Francis pump-turbine	
Type	Francis type single-stage reversible pump-turbine
Head	Maximum 431.80 m, Minimum 413.64 m
Number of units & unit size	2 units, 4.500 m
Turbine rotational speed range	350 min^{-1}, 381 min^{-1}
Mechanical power	Generating mode: 400 MW, 390 MW, 190 MW Pumping mode: -300 MW, -381 MW, -390 MW
Rated mechanical power	395 MW
Specific speed number	38 SI
Mechanical time constant	7.9 s
Motor-Generator	
Type of power generator	Asynchronous machine
Variable speed	DFIM
Rated power	420 MVA
Network frequency	50 Hz

3. Frades 2 PSPP modelling

3.1. SIMSEN modelling

To assess the compliance level of the DFIM technology against the set of ancillary services considered and to quantify corresponding performances, a 1D SIMSEN simulation model of the Frades 2 PSPP has been developed and validated. The model, which is illustrated in Figure 2, includes all the waterways and the two reversible Francis pump-turbines with their rotating mass inertia. The behavior of the reversible Francis pump-turbine is modelled with the 4-quadrants characteristics provided by the turbine manufacturer.

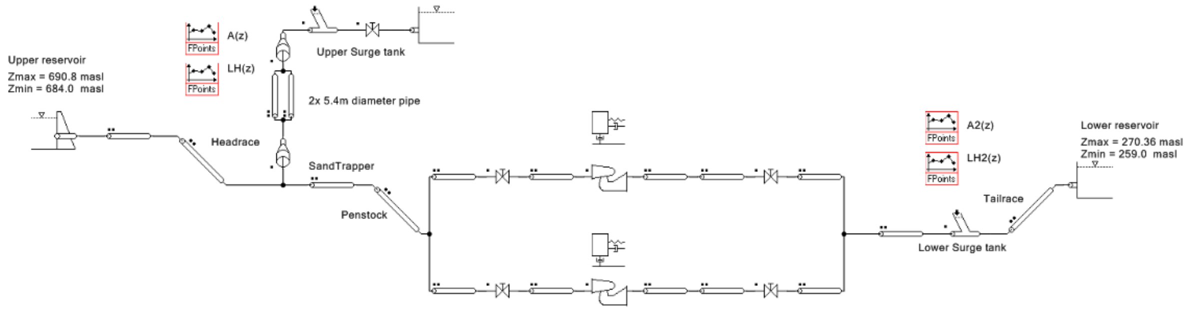

Figure 2 SIMSEN model of the Frades 2 PSPP.

The 1D model includes the control system related to variable speed technologies and allows to simulate the provision of Frequency Containment Reserve (FCR), Synthetic Inertia (SI), Fast Frequency Response (FFR) and automatic Frequency Restauration Reserve (aFRR) ancillary services. The control system parameters have also been optimized to achieve high control performance. Since the rotational speed of the variable speed drives is decoupled from the power network frequency, the ancillary services are reflected in a change of the power setpoint sent to the unit controller. Figure 3 illustrates the schematic block diagram of the active power set point modification due to frequency deviation. The aFRR service is translated to the nominal power setpoint P_o, which is independent of the grid frequency. The FCR branch generates a power setpoint change proportional to the grid frequency deviation with a first order transfer function defined by a time constant τ_P and a gain $K_p = -1/Bs$, where Bs is the permanent droop. The synthetic inertia response to the frequency RoCof is achieved by a first order transfer function defined by a time constant τ_d in series with a derivative term and a gain K_d which is set to correspond to the mechanical time constant of the unit τ_m [3-4]. The FFR ancillary service is represented with an independent branch, which activates a power step during a defined support duration when the frequency drops below a threshold.

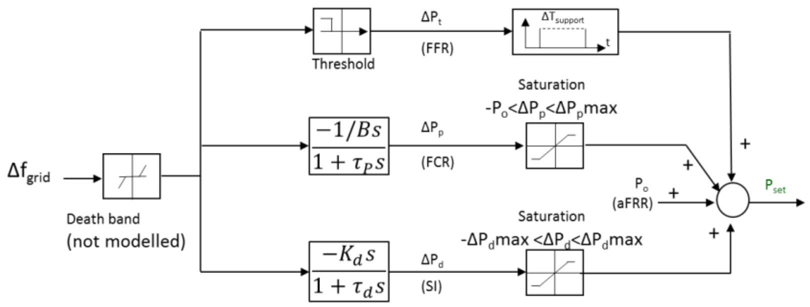

Figure 3 Schematic block diagram of the active power set point modification due to frequency deviation with primary regulation and inertia emulation services.

To quantify the capacity of ancillary services, the allowed operating range of the Frades 2 units must be considered as boundary condition for the simulations. In particular, with a minimum head, the normal operating range of the turbine mode varies from P_{min} = 186.4 MW to P_{max} = 372.8 MW, while in pump mode the input power can be varied from P_{min} = -300 MW to P_{max} = -390 MW. In addition to these power limitations, the DFIM technology features some inherent speed deviation limits due to the maximum voltage amplitude of the 1st harmonic (slip frequency) in the rotor winding. With the active power of the DFIM converter being equal to the slip power, the allowable speed range is limited by the power capacity of the frequency converter. In the case of Frades 2, the speed of the unit should remain within the steady speed range 350-381 min^{-1}. Outside this speed range, the power electronics cannot maintain the speed of the unit for long without overheating the electrical components. It is nevertheless accepted that the unit makes speed excursions of ± 10 min^{-1} outside the steady speed range during transients [12], which set the transient speed range between 340-391 min^{-1}. During the normal generating mode, the runner can be operated at any speed within the authorized range. One obvious strategy is to select the rotational speed n_{opt} which maximizes the turbine efficiency for a given power. The corresponding allowable speed range as a function of the power are represented in the Figure 4, with the steady speed range operation in green, the allowed transient speed in orange, and in blue the area delimiting the location of n_{opt}, which is bounded by the minimum and maximum head. It can be observed that, due to the admissible speed limitation, the optimal speed is equal to the minimum speed n_{min} = 350 min^{-1} over almost the entire power range, *i.e.* n_{opt} = n_{min} for 0<P<0.98 pu. Consequently, the available stored kinetic energy is limited when operating at n_{opt} = n_{min}, compared to a higher rotational speed, as illustrated by the arrows representing the allowed transient speed drop in Figure 4.

A simplified model is used to represent the electro-magnetic torque of the electrical machine, depending on actual speed and electrical power setpoint, without the need of complete hydro-electrical model, see [13]. The simplified model of a variable speed drive simply calculates the electro-magnetic torque from a given electrical power setpoint and the actual speed of the shaft. In order to take the existing delay between the setpoint change and the actual power output change into account, a first order low pass transfer function is considered, whose time constant is representative of the time response of the power converter and its power control. This simplified model has been validated against the detailed electrical model for DFIM variable speed and is hence used for variable speed simulation scenario.

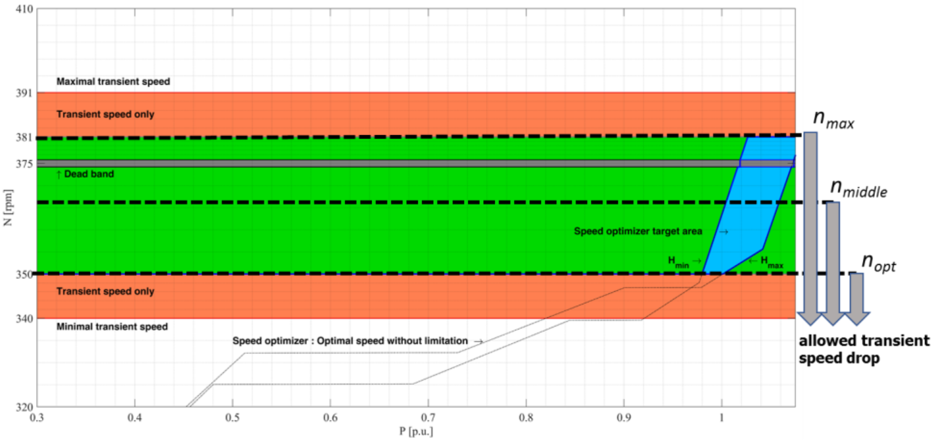

Figure 4 Frades 2 allowable speed range as function of the power with the best efficiency speed marked in blue. The arrows illustrate the maximum allowed transient speed drop as function of the initial rotational speed of the unit.

3.2. Variable speed control strategies

The variable speed technology allows to manage the power exchange with the grid with more flexibility than a conventional synchronous machine. In fact, two control strategies can be implemented to manage this power exchange. The first control strategy acts on the pump-turbine (PT) guide vane opening to regulate the power, while the power electronics of the motor-generator (MG) manage the speed of the unit, as schematized on the left side of Figure 5. Due to the different dynamic time constants between electrical and hydraulic parts, this strategy is preferred to ensure a desired speed response, but it can result in a large deviation between the power output of the unit and the set point during transients, as illustrated on the left of Figure 6. The second control strategy uses the power electronics to regulate the output power by managing the electromagnetic torque, while the rotational speed is controlled by the unit speed governor which manages the opening of the guide vanes, as schematized in the right hand side of Figure 5. This strategy is the main one used in turbine operation as it allows a fast power response of the unit to a load variation, while the speed can be adjusted more slowly by the guide vane to achieve optimal efficiency speed. However, depending on the requested change of the unit load, the unit rotational speed may exceed the allowable operating range, as shown on the middle of Figure 6. In that case, it is necessary to operate a strategy switch by taking advantage of the fast electromagnetic torque response of the power electronics to preserve the unit from over/under speed. The consequence of this strategy switch during a change of the power setpoint is illustrated on the right hand side of Figure 6. As it can be observed, the unit rotational speed stays within the allowable range. However, the output power profile presents a significant deviation from the requested power setpoint, which can be highly detrimental to grid stability. Therefore, switching strategies when providing ancillary services should be avoided as much as possible. All these control strategies have been integrated in the SIMSEN model of the Frades 2 PSPP and used to assess the plant control capability within the operating limits.

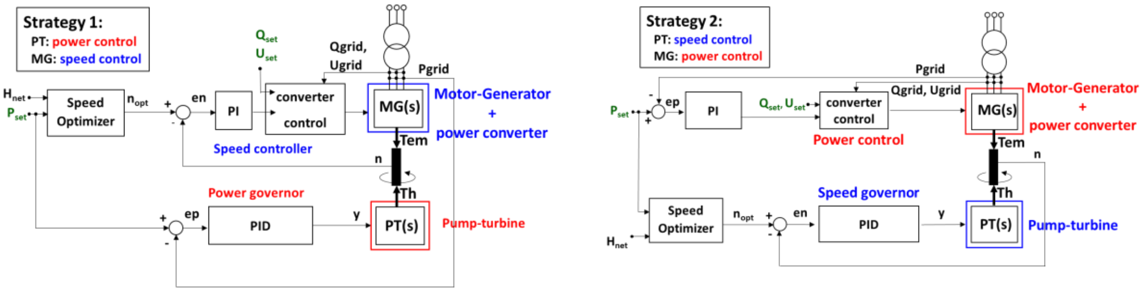

Figure 5 Schematic block diagram of the variable speed unit controller in turbine mode. a) Strategy 1: speed regulation with converter and power regulation with turbine. b) Strategy 2: speed regulation with turbine and power regulation strategy with converter.

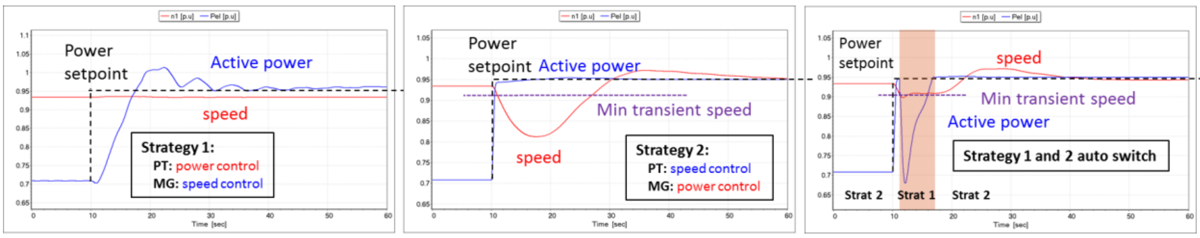

Figure 6 Example of power and speed responses to a power step with the different control strategies of a variable speed unit. Left: strategy 1, middle: strategy 2, right: automatic strategy switch to preserve the unit from under speed.

4. Simulation conditions and scenarios

The evaluation of the different ancillary services requires selecting grid codes, whenever applicable, or defining relevant metrics to quantify the contribution of the demonstrators and related technologies to the different ancillary services. The French Grid Code of RTE [14] has been selected for the evaluation of FCR capabilities, since its definitions are similar to the ones defined in the ENTSO-E document but include a complete description of the qualification test. The ENTSO-E grid code for Nordic Synchronous Area [15] was considered to evaluate FFR capability with the following requirements:

- The qualification test of FCR ancillary service imposes a step frequency deviation from the nominal value of -200 mHz and +200 mHz to the turbine controller as input. The output power response of the unit (Primary Control Reserve, *RP*) must respect the limitations defined in the grid codes, namely a time shorter than 2 s after which the power response is greater than the measurement uncertainty, and a time shorter than 30 s at which the power response reaches 95% of the primary reserve R_P.
- Regarding the FRR simulation, this ancillary service is activated by a frequency drop according to a step or a ramp. The qualification test events are defined as follows. The frequency drop is imposed and when frequency reaches the *activation level* threshold of 49.7 Hz (-0.3 Hz), the unit must deliver a power amplitude within a time of 1.3 s (*maximum full activation time)* and maintain it during 30 s (*minimum support duration*). Then, the frequency is restored to the nominal frequency and the unit goes back to its initial power level.

The assessment of the control capabilities for each ancillary service is performed under the most detrimental condition corresponding to the minimum head with the two 2 units responding simultaneously to frequency variations. Furthermore, the initial power set point of the unit is fixed to the maximum allowable value, corresponding to P_{max} minus the reserve power amplitude of the ancillary service considered. Thus, if the test is successful under these conditions, all other operating points are able to meet the requirements of that ancillary service.

5. Frades 2 FCR and FFR capacity assessment

5.1.1. FCR capacity

The FCR capacity is first evaluated with the most obvious approach for exploiting the variable speed unit, corresponding to using the converter for power control while the pump-turbine regulates the speed, i.e. strategy 2 in Figure 5. The speed optimizer will then target the rotational speed n_{opt} which maximizes the turbine efficiency for a given power. When a rapid injection of power into the grid is required, energy is transferred from the rotational kinetic energy of the inertia to the grid, which induces a decrease in the rotational speed of the unit, which is then compensated by the speed controller. However, under minimum head, the optimal speed is equal to the minimum rotational speed of n_{min}=350 min^{-1}. Consequently, the amplitude of the speed drop is limited before reaching the minimum transient speed of 340 min^{-1}, which then requires switching the converter to speed control mode to maintain the unit within the allowable range, at the expense of the power response sag. These considerations limit the amount of FCR power that the unit can provide. To illustrate this, the output power response to a frequency deviation of -200 mHz with the unit operated at the speed n_{opt} is shown in Figure 7, along with the corresponding unit transient behaviour. The permanent droop is set to 2 %, corresponding to a power response up to P_{max} under the minimum head. As expected, when a control strategy switch is operated to maintain the rotational speed within the allowable range, a large deviation of the power from the desired response set point is observed. Although in this case the power response is still above the gauge level, and therefore complies with the grid code, this would not be the case for larger FCR amplitude, which limits de facto the available reserve power.

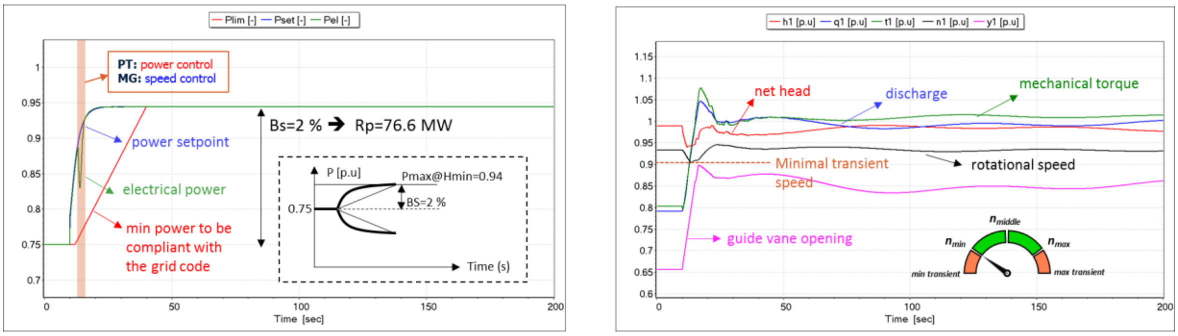

Figure 7 FCR in turbine mode – Output power response (left) and corresponding unit transient behavior (right) to a frequency deviation of -200 mHz with Bs = 2% and n_{ini}=n_{opt}= n_{min}.

In order to increase the FCR capacity, it can be advantageous to set the initial speed of the unit in the middle of the allowable range, n_{middle} = 365.5 min^{-1}, in order to have the maximum flexibility for under and over speed excursion, cf. Figure 4. The price to pay is a reduction of the pump-turbine efficiency of about 0.6 % due to non-optimal speed. Therefore, the HPP operators can choose whether the gain in flexibility from maximizing the allowed speed range is beneficial versus the efficiency loss it represents, depending on the conditions of the electricity market. The benefit of operating the unit at n_{middle} in terms of FCR capacity is immediate. In this setting, the FCR power band can be equal to the whole normal operating range of the power plant, corresponding to a permanent droop of *Bs=1.695%*, without reaching the minimum and maximum transient speed limits. Moreover, if adequate monitoring and thorough knowledge of the machine allows the plant owner to authorize temporary off-design operation such that P_{min} equals 0 MW in turbine mode, setting the initial speed of the unit at n_{middle} enables to drastically increase the contribution to FCR service to cover the full extended turbine operating range, which is the theoretical maximum possible. The output power response to a frequency deviation of ±200 mHz and corresponding unit transient behaviour with a permanent droop of *Bs=0.85 %*, yielding a FCR active power contribution of ±186.4 MW, is shown in Figure 8. It can be noticed that, in the case of a frequency deviation of + 200 mHz, a strategy switch with the motor-generator in speed control is

necessary to maintain the unit overspeed within the admissible limits. Nevertheless, the power response of the unit remains compliant with the grid code considered.
The fast dynamics of the power electronics allows the unit to swiftly follow load variations, which translate to a significant increase in ancillary service provision in variable speed as compared to the fixed speed technology. This is exemplified in Figure 9, considering a generic fixed speed control structure with parameters adjusted to optimize the unit. In this way, with the requirements of the selected grid code, the variable speed technology allows for 3.5 times higher FCR power reserve than with a corresponding fixed speed realization. In addition, variable speed technology enables to provide FCR service in pump mode. In the case of Frades 2, it is verified numerically that the FCR active power in pumping mode is able to cover the entire power range of the pump.

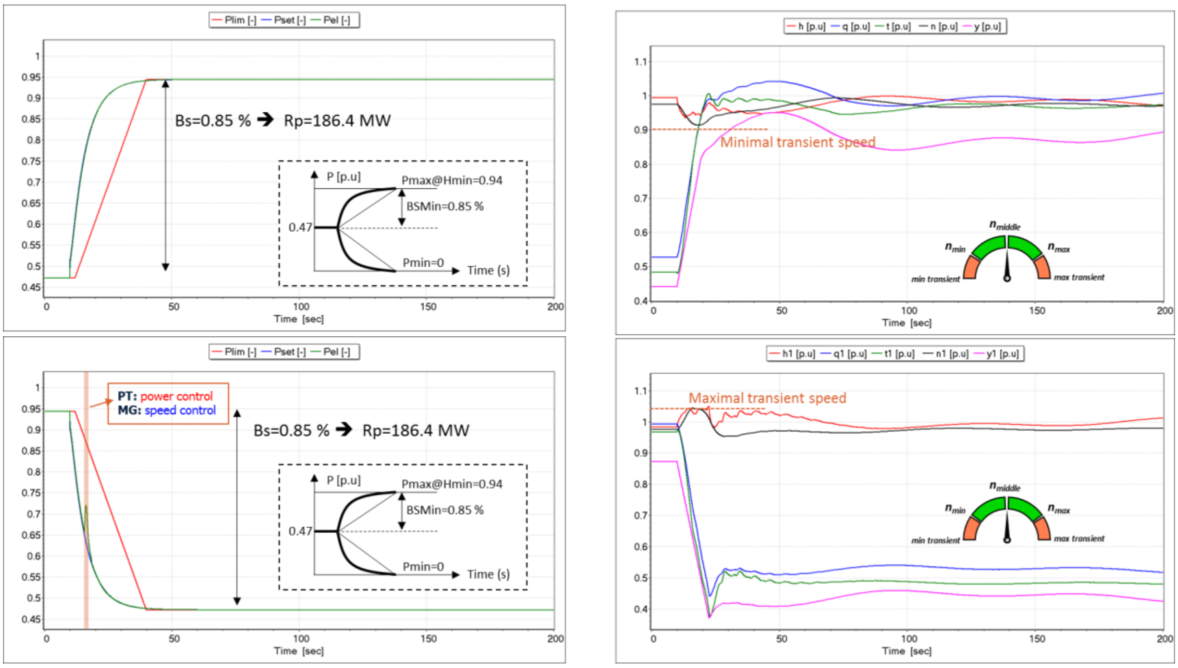

Figure 8 FCR in turbine mode - Output power response (left) and corresponding unit transient behavior (right) to a frequency deviation of ±200mHz with Bs=0.85% and $n_{ini}=n_{middle}$..

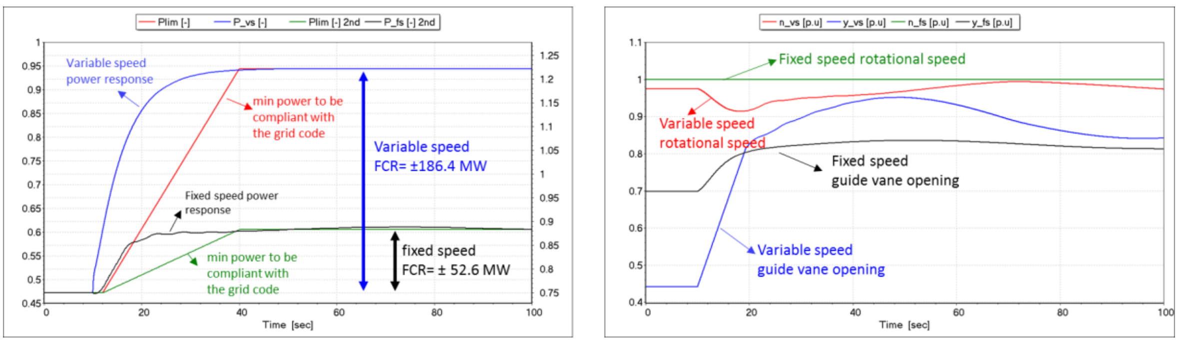

Figure 9 Variable speed vs fixed speed FCR power response (left) with the corresponding unit transient behavior (right) to a frequency deviation of ±200mHz.

5.1.2. *FFR capacity*

To assess the FFR capability, a frequency drop is imposed to the unit governor and when the frequency reaches the threshold of 49.7 Hz (-0.3 Hz), the unit must provide a power amplitude, called FFR capacity, within 1.3 s. This new active power must be maintained for 30 s. This situation is simulated with both units of Frades 2 operated in turbine mode under the minimum head and at an initial power equal to P_{max} at H_{min}, minus 1.2 times the FFR capacity. When the power converter supplies power to the network by modifying the electromagnetic torque applied to the pump-turbine, the unit undergoes a drop in speed, which is then compensated in a second time by the speed governor of the pump-turbine, whose dynamics is slower than the converter. Due to the slower dynamic associated with the pump-turbine regulator, it must be checked that the speed deviation remains within the speed constrains inherent to DFIM technology. These considerations open the door to different possible strategies of turbine operation for the provision of FFR service. For instance, the turbine can be operated at the speed which maximizes the unit efficiency $n_{opt=}n_{min}$, the middle speed n_{middle}, which maximizes the FCR capacity, or the speed n_{max}, which maximizes the energy stored in the rotating masses.

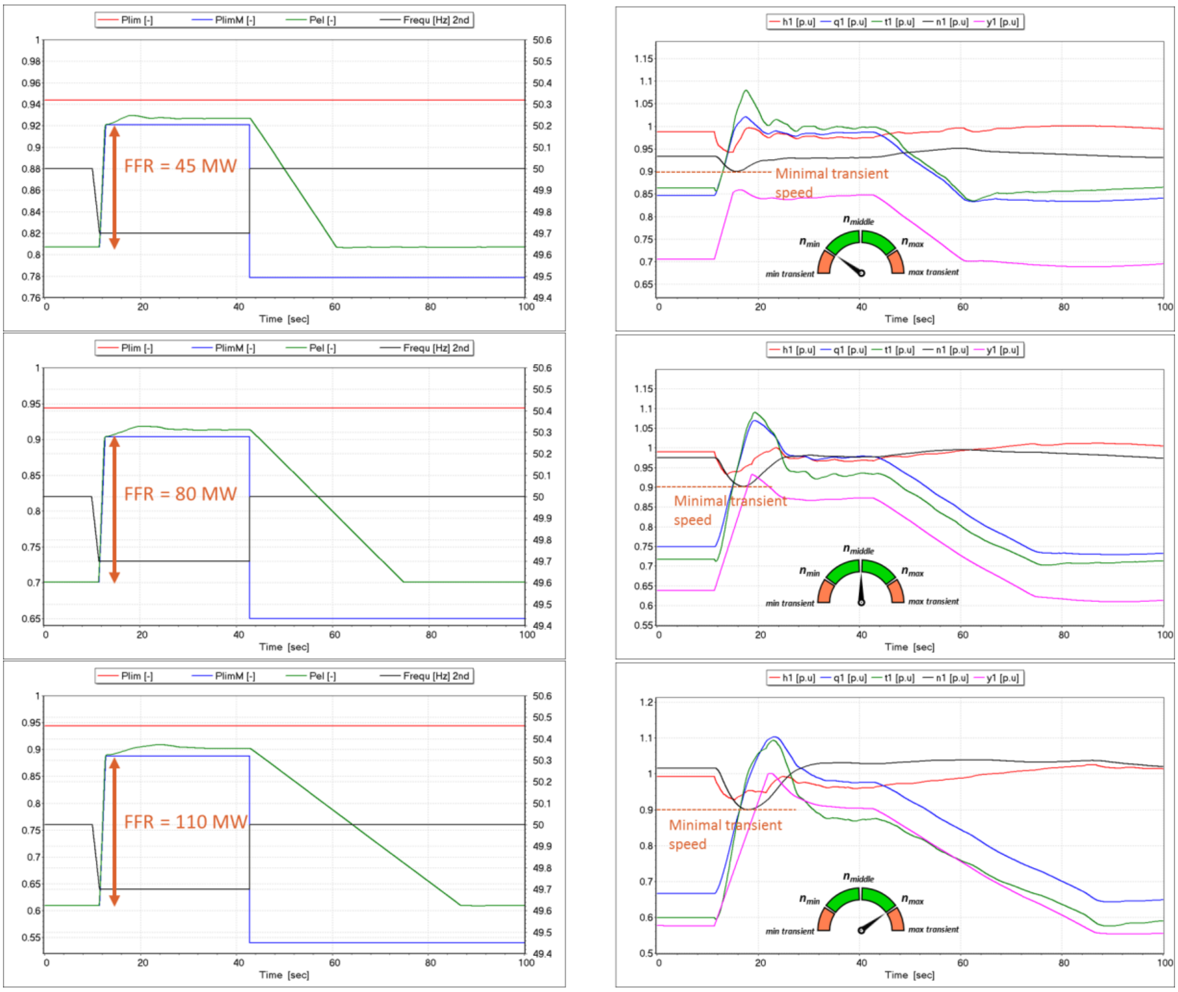

Figure 10 FFR in turbine mode with initial speed at n_{min} (Top) - n_{middle} (middle) - n_{max} (bottom) Output power response (left) and corresponding unit transient behavior (right)

The results for the maximum FFR capacity assessment in turbine mode related with each initial speed of the unit are shown in the Figure 10. For each case, the power step that brings the machine just above the minimum allowable transient speed is targeted. In order to optimize this behaviour, and not to cause a more severe speed drop than necessary, the power setpoint transmitted to the machine is ramped with a slope corresponding to the requirement of the grid code, *i.e.* 1.3 s for 100% of the FFR power supplied. In the same spirit, when the frequency is restored after 30 s, the power setpoint used to bring the unit back to its initial power level features a slow slope, to avoid an overspeed of the unit beyond the admissible value. The FFR capacity of each unit in turbine mode is thus equal to 45 MW, when the units are operated initially at n_{min}, 80 MW if the initial speed is set at the middle speed n_{middle} , and up to 110 MW delivered in 1.3 s, if the initial speed is at n_{max}, which is remarkable. In addition, regarding the FFR capacity with both units in pump mode, it is verified numerically that, using the power converter to control the input power of the pump, the variable speed units are able to decrease their load by the full pump operating range of 90 MW within the 1.3 s required by the grid code.

6. Conclusions

The maximum contributions of the Frades 2 pumped storage power plant to FCR and FFR ancillary services has been evaluated using a 1D SIMSEN simulation model of the plant with the appropriate variable speed control structures. Thanks to the fast dynamics of the power electronics allowing the unit to swiftly follow load variations, a significant increase in ancillary service provision can be achieved with the variable speed technology as compared to the fixed speed technology.

It was shown that, setting the rotational speed to the value corresponding to the middle of the available speed range, instead of the optimal rotational speed, improves FCR services. The FCR power band can then be equal to the whole operating range of the power plant, corresponding to the notable maximum active power contribution of ±186.4 MW in the case of Frades 2 in turbine mode. The price to pay is a slight reduction of the pump-turbine efficiency due to non-optimal speed. Therefore, HPP operators can choose to maximize either unit efficiency or FCR service depending on the electricity market conditions.

Moreover, the variable speed technology allows to address FFR service, in both turbine and pump mode, which is not the case of fixed speed due to the fast dynamics needed to meet the service requirements. By choosing an operating strategy which maximizes the energy stored in the rotating masses, it is established that an active power steps of +110 MW and +90 MW performed within 1.3 s can be achieved respectively in turbine and pump mode, which is remarkable.

7. Acknowledgements

The Hydropower Extending Power System Flexibility (XFLEX HYDRO) project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 857832.

References

[1] https://xflexhydro.net/

[2] XFLEX HYDRO - Deliverable D2.1, Flexibility, Technologies and scenarios for hydro power, INESC TEC, 2020.08.01,

[3] L. N. Papangelis et C. D. Vournas, « Design Principles of Wind Turbine Inertia Emulators for Autonomous Systems », *IFAC Proceedings Volumes*, vol. 47, nº 3, p. 5844-5851, 2014.

[4] A. Wickramasinghe, L. Meegahapola, A. P. Agalgaonkar, et S. Perera, « Design considerations for inertia emulating controllers used in variable speed wind turbines », in *2014 IEEE PES General Meeting | Conference & Exposition*, National Harbor, MD, USA, juill. 2014, p. 1-5.

[5] A. Béguin, C. Nicolet, J. Hell, et C. Moreira, « Assessment of power step performances of variable speed pump-turbine unit by means of hydro-electrical system simulation », *J. Phys.: Conf. Ser.*, vol. 813, p. 012001, avr. 2017.

[6] J. Hell, M. Egretzberger, et A. Lechner, « Grid Frequency Response–Contribution of Hydro-Power for Grid Stabilization », *HYDRO conference Cernobbio*, 2014.

[7] Kopf, E., Brausewetter, S., Giese, M., Moser, F., “Optimised control strategies for variable speed machines,” In Proceeding of the 22nd IAHR Symposium on Hydraulic Machinery and Systems, Stockholm, Sweden, June –July 2004.

[8] Kuwabara, T., Shibuya, A., Furuta, H., Kita, E., Mitsuhashi, K., "Design and Dynamic Response Characteristics of 400 MW Adjustable Speed Pumped Storage Unit for Ohkawachi Power Station", IEEE Transactions on Energy Conversion, vol. 11, issue 2, pp. 376-384, June 1996.

[9] Nicolet, C., Pannatier, Y., Kawkabani, B., Schwery, A., Avellan, F., Simond, J.-J., "Benefits of Variable Speed Pumped Storage Units in Mixed Islanded Power Network during Transient Operation", Proceedings of HYDRO 2009, in Lyon, France.

[10] Pannatier, Y., Kawkabani, B., Nicolet, C., Simond, J.-J., Schwery, A., Allenbach, P., "Investigation of control strategies for variable speed pump-turbine units by using a simplified model of the converters", IEEE Transactions on Industrial Electronics, Volume: 57, Issue: 9, 2010, pp: 3039-3049.

[11] A. Schwery, T. Kunz, et S. Gökhan, « Adjustable speed pumped storage plants–Innovation challenges and feedback of experience from recent projects », *Hydrovision International, Louisville, KY, USA*, 2012.

[12] Koutnik, J., "Frades II-variable speed pumped storage project and its benefit to the electrical grid", in *Proc. Int. Conf. Renewable Energy*, 2012, p. 1-7.

[13] C. Nicolet, O. Braun, N. Ruchonnet, A. Beguin, J. Hell, et F. Avellan, « Full size frequency converter for fast Francis pump-turbine operating mode transition », *Proceedings of HYDROVISION International 2016 (Minneapolis, MN, USA, July 26-29 2016)*, 2016.

[14] RTE, Documentation Technique de Référence, Chapitre 8 Trames Types, Article 8.3.3 Trame de procédure de contrôle de conformité pour le raccordement production, Version 2.1 applicable à compter du 31/03/2021, pp. 63-69.

[15] ENTSO-E, "Technical Requirements for Fast Frequency Reserve Provision in the Nordic Synchronous Area External document", 11 January 2021.