XFLEX HYDRO Task 2.4 – Models' documentation (Milestone 3)

Milestone 3 – Release of hydropower reduced order models for each technology/solution

1. Context

The overarching objective of XFLEX HYDRO project is to develop and demonstrate new technological solutions capable of being integrated in different types of Hydro Power Plants (HPP) aiming to improve its efficiency and performance with respect to the provision of different Electric Power Systems (EPS) services. The past activities developed within the scope of Work Package 2 - *WP2: Flexibility services and specification* - concerned the identification of the framework for the provision of flexibility services in future EPS by HPP. In particular, it was performed a detailed assessment of current and emerging flexibility services for EPS, as documented in the Deliverable D2.1 [1].

Aiming to evaluate the performance of different hydroelectric technologies and solutions under development in the XFLEX HYDRO demonstrators, a wide range of detailed engineering studies were performed resorting to 1D time domain simulations in order to quantify the magnitude of the flexibility products and to characterize the corresponding dynamic response over time. Such evaluation if of utmost importance regarding the need of validating the performance of the different technological solutions applied in each demonstrator with respect to the technical specification of the flexibility products under evaluation.

Following the progressive integration of the hydropower technologies in the EPS, it is necessary to identify and consolidate proper simulation models in order to evaluate the resulting impact regarding the system dynamic performance. Hence, within the basket of flexibility products addressed in WP2, those related to active power balancing (automatic frequency restoration reserve) and power-frequency regulation (synthetic inertia, fast frequency response and frequency containment reserve) were selected for this purpose. With respect to fixed speed HPP, the proposed models were selected among those widely available in the literature and existing also in different EPS simulation packages. Regarding variable speed HPP (or any type of technology relying in a power electronic interface for grid connection), it was proposed models resorting to an approximation of the physical component's dynamic response by simpler transfer functions with the corresponding limits. Such a modelling approach is intended to properly reflect the physical components interaction with the grid without exhaustively representing all the physical phenomena taking place.

As a main outcome of this work, it was identified and validated, within the scope of the project demonstrators, hydropower reduced order dynamic models capable of representing the provision of the aforementioned flexibility services under different conditions. The identification and consolidation of these models follows a grey box approach: the model architecture/block diagram representing the main dynamics of the unit power response is assumed *a priori*; then, the set of parameters and limits for each model were identified resorting to an advanced algorithm to best fit the proposed model response to the 1D time domain simulation of the different demonstrators and associated technologies. The model parametrization fitting to 1-D time domain simulations may require different sets of parameters for best reproducing the dynamic response associate to different services. Hence, the obtained results demonstrate the ability of the proposed models to properly represent the main dynamics of the studied HPP and associated technologies with respect to specific grid services.

The project demonstrators for which the reduced models were identified with respect to the flexibility services are the following:

- Z'Mutt;
- Frades 2;
- Grand-Maison;
- Alqueva;
- Alto Lindoso;
- Vogelgrün.

A proper description of the main characteristics of the demonstrators can be found in Deliverable D2.1 [1], together with the envisioned tectological options under evaluation in each case. In the next chapters the following contents are presented:

- Summary of the ancillary services under evaluation;
- Hydro power technologies being accessed;
- Proposed set of hydro power plant models;
- Summary list with model's documentation per demonstrator and associated technology (when applicable).

2. Ancillary services under evaluation

The Ancillary Services Matrix evidences a wide range of ancillary services being exploited for EPS operation. Considering the active power balancing and active power-frequency regulation mechanisms, four services (detailed requirements and characteristics presented in [1]) were selected for being addressed in terms of model identification, considering their relevance with respect to a wide range of EPS studies addressing system dynamic performance:

- Synthetic inertia (SI);
- Fast Frequency Response (FFR);
- Frequency Containment Reserve (FCR);
- Automatic Frequency Restoration Reserve (aFRR).

The inherent characteristic of synchronous units (fixed seep type) for providing (synchronous) inertia to the electric power system is not addressed in this document as it is well stablished in the literature and can be easily represented based on the classic swing equation. The proposed reduced order models for HPP aim to properly reproduce the main dynamics of the power response in each demonstrator while considering different technological options. In order to test the provision of each service previously referred, input signals need to be provided to the envisioned models, hence mimicking a certain behaviour of the grid frequency (fset) regarding the SI, FFR and FCR services or an active power setpoint (Pset) for the provision of the aFRR service. A brief reference to the main characteristics of the aforementioned services and input signals for simulating its activation are described hereafter. The operating conditions considered for evaluating the response of HPP with respect to the envisioned ancillary services were defined to ensure the most constraining conditions for the hydraulic power plant. Thus, the reported models and associated results evidence the capability of a given demonstrator/technological option to successfully respond to a given service. Being the response compliant with the service requirements under these operating conditions, all operating points will be able to comply with this ancillary service requirements.

2.1. Synthetic Inertia (SI)

The Commission Regulation 2016/631 of 14th April 2016, establishing a network code on requirements for grid connection of generators, defines 'synthetic inertia' as the capability provided by a power park module to replace the effect of inertia of a synchronous power-generating module to a prescribed level of performance. In general, system inertia has a major impact in the rate at which the grid frequency varies – Rate of Change of Frequency – *RoCoF* (Hz/s) following a system incident. Hence, the considered input signals to test this service deployment from a given plant consisted in a positive and negative frequency deviation from 50 Hz with a RoCoF of 1 Hz/s (0.02 p.u./s) in the frequency setpoint (fset) at the speed controller – the current maximum capability in CE power plants [2] resulting in the frequency deviation signal (Δf = fgrid - fset) being presented in Figure 1.

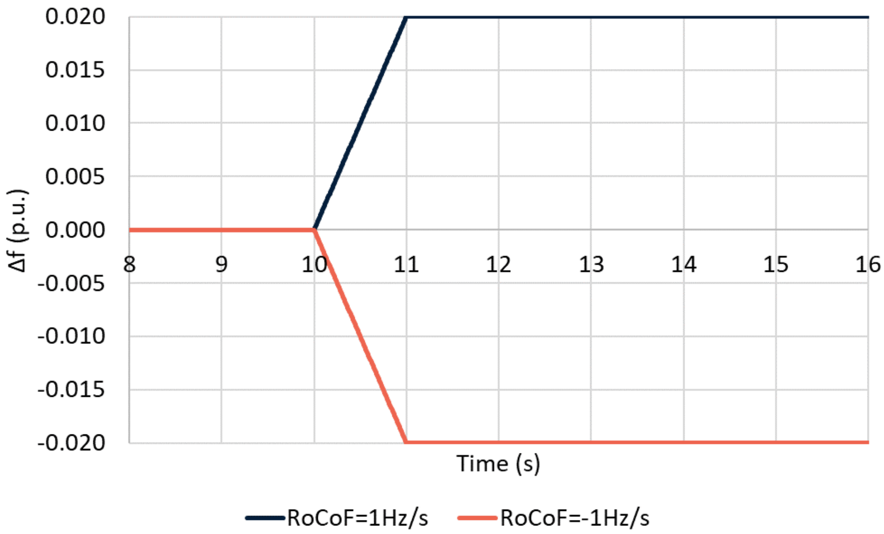

Figure 1 – SI input signals: frequency deviation ramps with a RoCoF of ±1 Hz/s (±0.02 p.u./s)

2.2. Fast Frequency Response (FFR)

FFR is usually designed to provide an active power response faster than existing operating reserves, typically in less than 2 seconds, in the timeframe following inertial response (i.e., typically after 500 ms) and before activation of the frequency containment reserve service (which has a maximum delay of 2 seconds). Also emerging from reducing system inertia and increased *RoCoF*, it is verified that conventional frequency containment reserves start to have a more constrained operation time windows to have an effective response to limit the frequency nadir/zenith to the prescribed range in a given area. A detailed specification of this ancillary service can be found in an ENTSO-E document for the Nordic Synchronous Area [3] which was therefore selected for FFR service requirements and associated quantification.

This ancillary service is activated by a frequency drop overpassing a given frequency activation level. The *maximum full activation time* must respect one of the following 3 alternatives according to the *activation level*:

- The maximum time for full activation is 0.70 s for the activation level 49.5 Hz.
- The maximum time for full activation is 1.00 s for the activation level 49.6 Hz.
- The maximum time for full activation is 1.30 s for the activation level 49.7 Hz.

The service provider may choose any of the three alternatives, but the choice must be specified beforehand. In this document, the third option was selected (maximum activation time = 1.30 s).

According to [3], during the *activation time*, the unit must reach the delivering of a power amplitude, named *FFR capacity*, and maintain it during the *minimum support duration* time of 5.0 s (for short support duration) or 30 s (for long support duration), see Figure 2. A *maximum acceptable overdelivery* is fixed to 20% of the prequalified FFR capacity. However, the reserve connecting TSO may allow up to 35% overdelivery upon request, depending on the national procurement process. Irrespectively, the duration of the FFR providing entities full FFR provision cycle must be shorter than 15 minutes, in order to be ready for a new activation. Finally, there is no limitation on the rate of deactivation for the long support duration FFR.

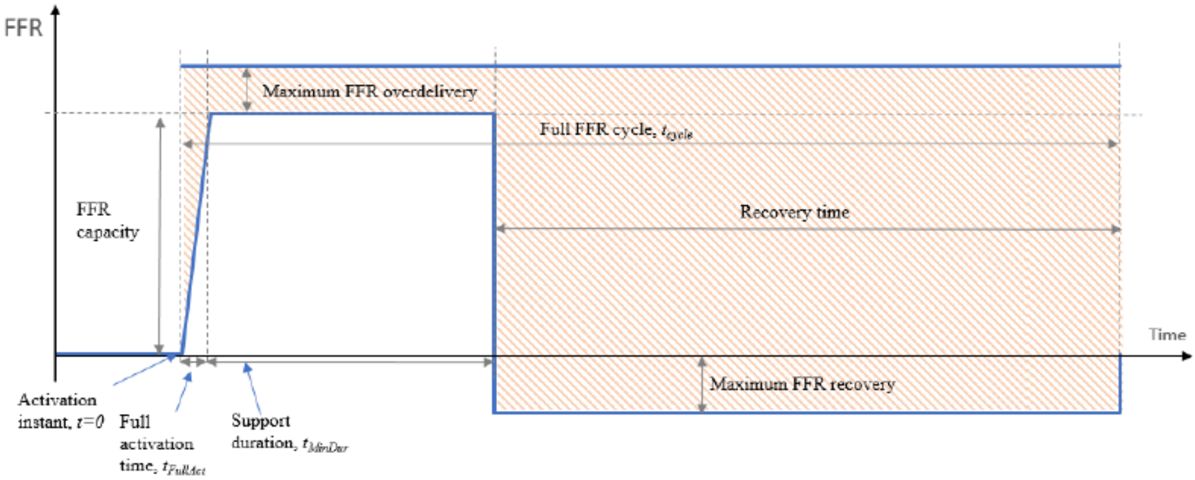

Figure 2 – FFR service response envelope [3]

Assuming a frequency activation level of 49.7 Hz (with the corresponding full activation time of 1.30 s), the input signal to test the deployment of this service was a frequency step of 300 mHz (0.006 p.u.) in the frequency setpoint (fset) at the speed controller, resulting in the frequency deviation signal (Δf = fgrid - fset) from 50 Hz to 49.7 Hz, as presented in Figure 3.

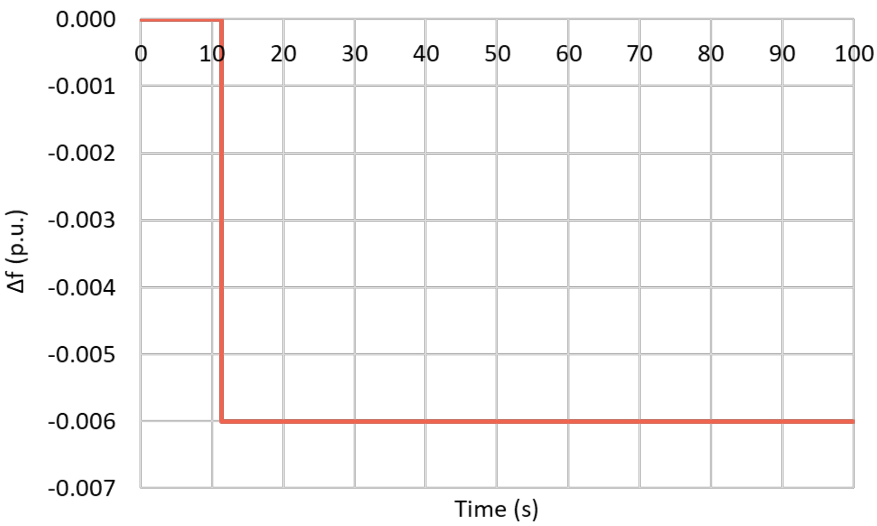

Figure 3 – FFR input signal: frequency deviation step from 0 to -300 mHz (-0.006 p.u.)

2.3. Frequency Containment Reserve (FCR)

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 and aiming to comply with pre-defined frequency time domain metrics. For FCR providers in the Continental Europe (CE) Synchronous Area (SA), the service has a maximum delay of 2 seconds, 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 TSOs of each SA).

The grid code of the French transmission system operator (RTE - *Réseau de Transport d'Électricité*) [4] was selected to evaluate FCR service, since this document contains a complete description of the qualification test and its definitions are similar to those provided by ENTSO-E.

For FCR service, the input signals used to test it were positive and negative frequency steps of 200 mHz (0.004 in p.u.) in the frequency setpoint (fset) at the speed controller, resulting in the frequency deviation signal (Δf = fgrid - fset) as shown in Figure 4.

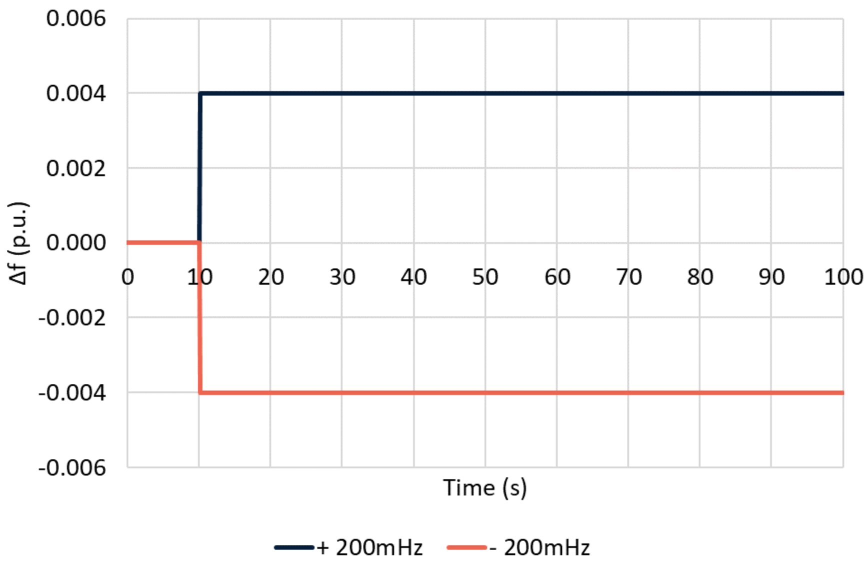

Figure 4 – FCR input signals: frequency deviation steps of ±200 mHz (±0.004 p.u.)

2.4. Automatic Frequency Restoration Reserve (aFRR)

The aFRR service consists in an automatic process aiming to restore the system frequency back to its set point (normal) value and to keep the power interchange program among load-frequency control (LFC) areas. The grid code of the French transmission system operator (RTE) [4] was also selected to evaluate aFRR service, since this document contains a complete description of the qualification test and its definitions are similar to the ones defined in the ENTSO-E document.

For aFRR service, the input signals used to test it were power setpoints ramp signals, with a duration of 300 s, from the minimum to the maximum technical power regulating range and vice-versa, as presented in Figure 5.

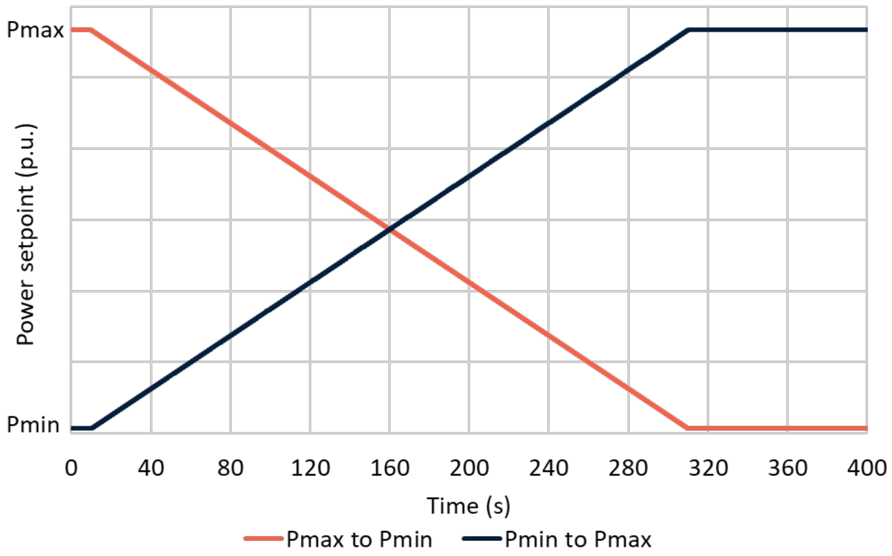

Figure 5 – aFRR input signals: 300 s power setpoint ramp from minimum to maximum and vice-versa

3. Modelled technologies

The developed models represent the technologies/combination of technologies that are being assessed and/or implemented throughout the XFLEX HYDRO project, as explained in [1] and summarized as follows:

- **Fixed speed** units, hydro power plants equipped with fixed speed synchronous machines;
- **Variable speed**, through the installation/conversion to Doubly Fed Induction Machine (DFIM) or Full-Size Frequency Converter (FSFC);
- **Smart Power Plant Supervisor** (SPPS), an advanced methodology to provide an adequate monitoring and extensive knowledge of the machine that will enable the plant owner to manage the risks and costs associated to a temporary off-design operation according to the potential benefits it offers. Hence, the inclusion of a SPPS unlock a wider operation range of the units, in general larger than those considered in the design phase. In this project, SPPS methodology is considered as an umbrella of all the actions, studies and control measures performed to increase the controllability and monitoring of the HPP without the installation of significant hardware;
- **Hydraulic Short Circuit** (HSC), which allows the hydro power plant (HPP) to operate at the same time a turbine in parallel to a pump. In case of fixed speed units, this enables the simultaneous operation of a pump at constant power and while performing power control with the turbine, varying continuously the consumption of the plant. When variable speed is considered, the operating range of the pump and of the turbine can be combined to further extend the overall operating range;
- **Hydro-Battery-Hybrid** (HBH), namely the hybridization of the HPP through the installation of a Battery Energy Storage System (BESS) for the provision of FCR services.

A proper description of this set of technologies to be implemented in different demonstrators can be found in [1]. Based on the developed work and results obtained from extensive 1-D time domain simulations, the following assumptions were made regarding the SPPS and HSC modelling:

- The inclusion of the SPPS technology unlock the operating range of hydro units, when working in turbine mode, to a larger range (from zero to maximum power for a given head) during a time period at least compatible with the time frame associated to the services under evaluation.

In pumped storage plants, pump operation mode is not affected by the SPPS since it is technically limited by intrinsic hydraulic constraints.

- The HSC enables fixed speed turbines to provide FCR and aFRR ancillary services when the power plant is in pump mode operation, being pumps operated at constant power;
- For variable speed, the HSC enables to aggregate the services provided simultaneously by the pump and turbine units.

4. Proposed dynamic models

The proposed set of models capable of reproducing the main dynamic response of the units with respect to different ancillary services follow two distinct approaches:

- For the fixed speed technology (with or without SPPS and/or considering the operation in HSC), the models were based on the state-of-the-art structures available in the literature and widely used in commercial software suits for EPS studies. The selected models are IEEEG3, HYGOV and PIDGOV [5]. In the performed simulations for assessing the performance of these models, the electrical frequency is assumed constant and imposed by the power system. The model response to frequency events was achieved by an artificial injection of the frequency signals presented in Figure 4 to the models' frequency input. These types of models usually have as output the mechanical power of the unit, which is then used to feed the electric generator dynamic model. Hence, in this work the approach focused on the validation of the model ability of properly represent the response with respect to the mechanical power output of the unit.
- For technological options encompassing the use of advance power conversion stages based on power electronic interfaces (such as the battery energy storage system for HPP hybridization and variable speed technology), the aim of associated models' development concerns the identification of generic control structures tailored to reproduce the main dynamics of the active power response that is provided to the power system. Therefore, for these models, the relevant power response is the electrical active power output (Pele). Like in fixed speed technology, in the performed simulations for assessing these models, the electrical frequency was assumed to be imposed by the power system and equal to the nominal value. The model response to frequency events is achieved by an artificial injection of the frequency signals presented in Figure 1, Figure 3 and Figure 4 to the model's frequency input.

In the developed models, all the values are in per unit (p.u.) regarding to the machine MVA base (Sn) and to the nominal frequency of the grid (50 Hz).

4.1. Fixed speed technology models

4.1.1. FCR and aFRR provision models

For representing the dynamic response of the speed governor and turbine of a fixed speed hydro machine (with or without SPPS and/or in Hydraulic Short-Circuit mode), three alternative models were selected from the existing literature: the IEEEG3, PIDGOV and HYGOV models [5]. The model parameters were tuned to fit the 1-D time domain responses for the different demonstrators regarding the provision of FCR and aFRR services (when applicable). The considered control structure for these models is described next.

4.1.1.1. IEEEG3 model

As presented in Figure 6, the IEEEG3 based model uses a turbine governor structure featuring permanent and transient droop, including a hydraulic turbine model based on a first order transfer function. A detailed description of this model can be found in [5].

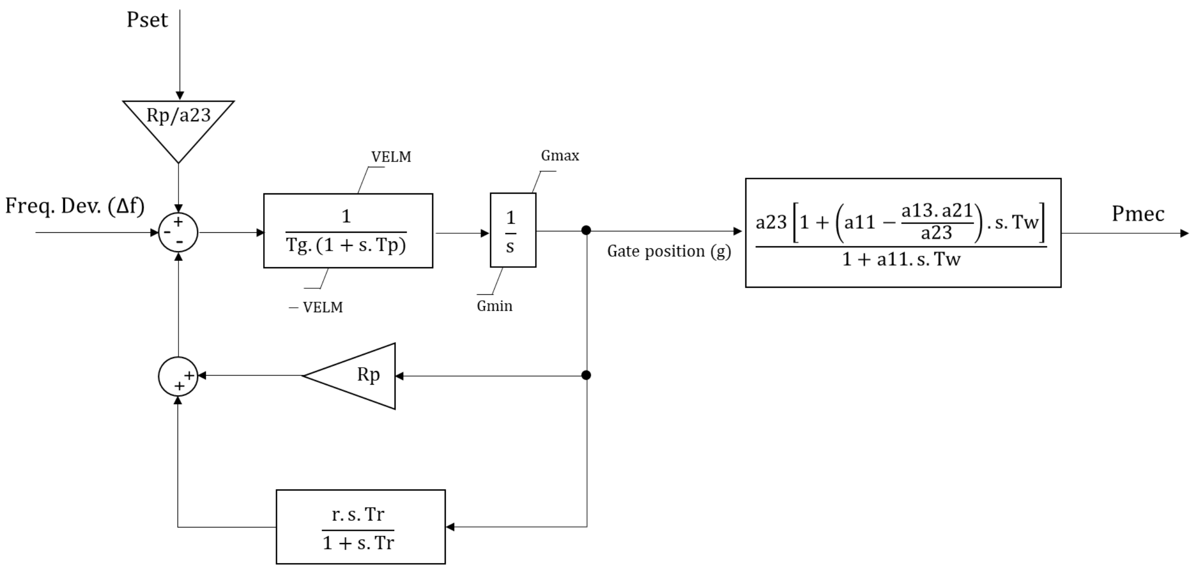

Figure 6 – Fixed Speed technology control structure for FCR and aFRR provision based on IEEEG3 model

The input signals are:

- Pset – active power setpoint (p.u.);
- Δf – grid frequency deviation from setpoint, given by fgrid - fset (p.u.).

The output signal is:

- Pmec – mechanical power (p.u.).

The model's parameters are:

- Rp – permanent droop (p.u.);
- r – transient speed droop (p.u.);
- Tr – governor time constant (s);
- Tp – pilot value time constant (s);
- Tg – gate servomotor time constant (s);
- VELM – gate velocity limit (p.u./s);
- Tw – water starting time constant (s);
- a11, a13, a21 and a23 – penstock coefficients;
- Gmax – maximum gate opening (p.u.);
- Gmin – minimum gate opening (p.u.).

4.1.1.2. PIDGOV based model

The PIDGOV based model, which is presented in Figure 7, is an alternative model using a PID structure, in line with typical real turbine speed governing systems [6] to represent the speed governor in a hydropower turbine and comprising a linear and ideal turbine model (the simplest way to represent hydraulic dynamics in power system studies). It is properly described and characterized in [5].

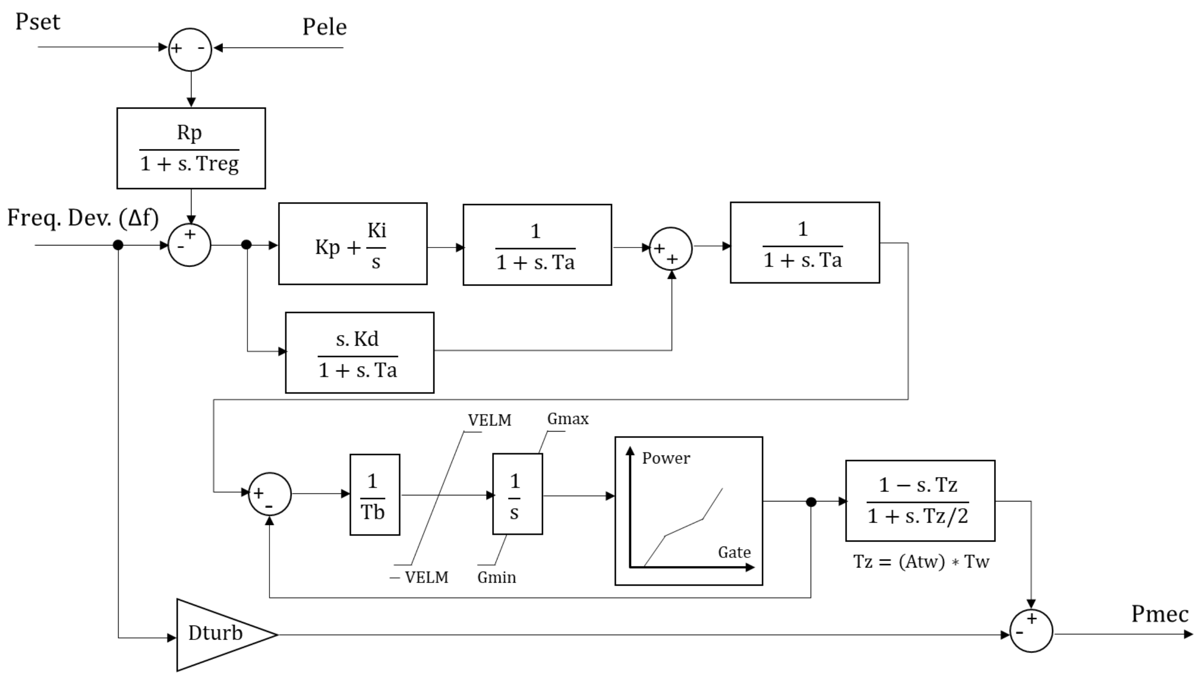

Figure 7 – Fixed Speed technology control structure for FCR and aFRR provision based on PIDGOV model

The input signals are:

- Pset – active power setpoint (p.u.);
- Δf – grid frequency deviation from setpoint, given by fgrid - fset (p.u.).

The output signal is:

- Pmec – mechanical power (p.u.).

The model's parameters are:

- Rp – permanent droop (p.u.);
- Treg – governor time constant (s);
- Kp – proportional gain (p.u.);
- Ki – integral gain (p.u./s);
- Kd – derivative gain (p.u.);
- Ta – controller time constant (s);
- Tb – gate servomotor time constant (s);
- Tw – water starting time constant (s);
- Atw – Tw multiplying factor (p.u.);
- Dturb – turbine damping (p.u.);
- VELM – gate velocity limit (p.u./s);
- Gmax – maximum gate opening (p.u.);
- Gmin – minimum gate opening (p.u.);
- P(y) – power (p.u.) to gate (p.u.) curve.

4.1.1.3. HYGOV based model

The HYGOV is one of the most used models to represent, in EPS studies, the dynamics of the speed governor in a hydropower plant and it is properly described and characterized in [5]. As presented in Figure 8, this model follows a permanent and transient droop control structure and includes a nonlinear model to represent the hydraulic system (the most detailed hydraulic model among the three alternative tested models).

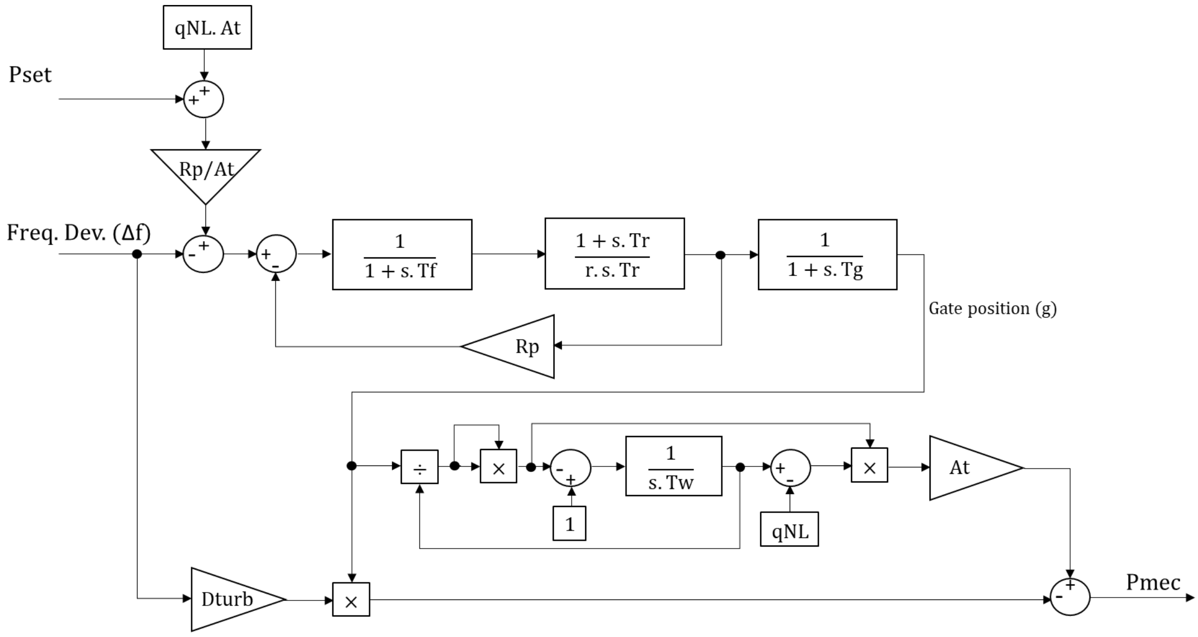

Figure 8 – Fixed Speed technology control structure for FCR and aFRR provision based on HYGOV model

The input signals are:

- Pset – active power setpoint (p.u.);
- Δf – grid frequency deviation from setpoint, given by fgrid - fset (p.u.).

The output signal is:

- Pmec – mechanical power (p.u.).

The model's parameters are:

- Rp – permanent droop (p.u.);
- r – transient speed droop (p.u.);
- Tr – governor time constant (s);
- Tf – filter time constant (s);
- Tg – gate servomotor time constant (s);
- VELM – gate velocity limit (p.u./s);
- Tw – water starting time constant (s);
- At – turbine gain (p.u.);
- Dturb – turbine damping (p.u.);
- qNL – no load water rate (p.u.);
- Gmax – maximum gate opening (p.u.);
- Gmin – minimum gate opening (p.u.).

4.1.2. Hydro-battery-hybrid technology for FCR provision

The model regarding the hydro-battery-hybrid (HBH) technology for fixed speed plants combines the contribution provided by the fixed speed unit with the active power output from a battery energy storage system controlled by a power converter coupling this system to the grid. This HBH model was developed for the specific case of the Vogelgrün demonstrator, a Run-of-River power plant, for the provision of FCR service. As presented in Figure 9, the model featuring the power contribution from the energy storage system comprises an active power response step with a magnitude equal to the battery rated power (Pn), with a delay and triggered by a frequency deviation outside a given deadband. This active power response has a fixed support duration time of Tdur seconds and is deactivated with a decay time constant Tc.

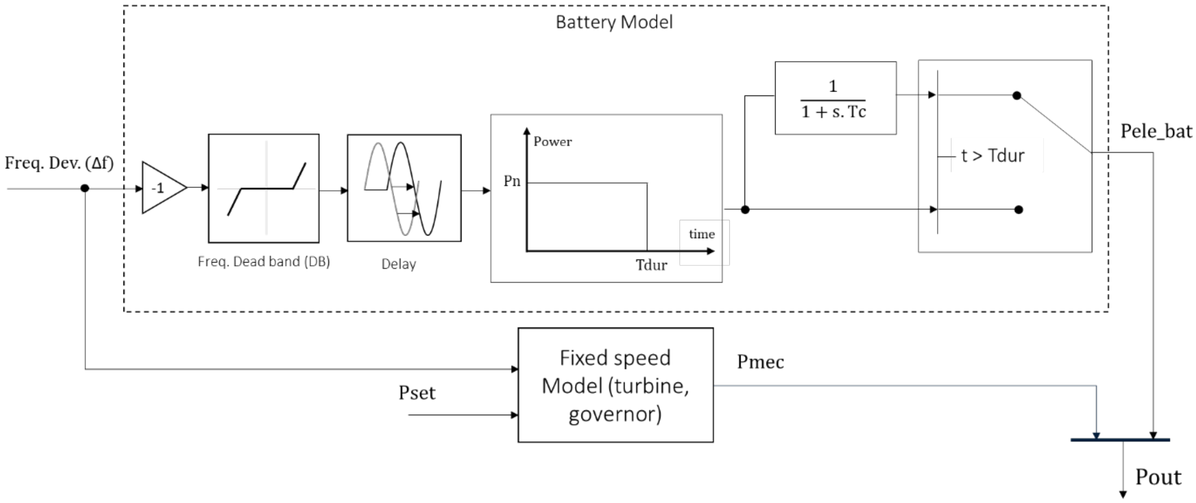

Figure 9 – Hydro-battery-hybrid technology control structure for FCR provision

The input signals are:

- Pset – active power setpoint (p.u.);
- Δf – grid frequency deviation from setpoint, given by fgrid - fset (p.u.).

The output signal is:

- Pele_bat – battery electrical active power output (p.u.);
- Pmec – mechanical power (p.u.).
- Pout – active power output of the Hydro-battery-hybrid model (p.u.)

The model's parameters are:

- Fixed speed model parameters (from IEEEG3, PIDGOV or HYGOV model);
- Pn – battery rated power (p.u.);
- DB – frequency deadband (p.u.);
- Tc – decay time constant (s);
- Tdur – support duration time (s).

4.2. Variable speed technology models

For the variable speed (with or without SPPS), a distinct model was considered for the provision of the following ancillary services:

- Synthetic Inertia (SI);
- Fast Frequency Response (FFR);
- FCR and aFRR.

The same control structure was assumed for the turbine and pumping mode operation of the reversible turbine and independently of having the SPPS in operation. This results from the fact that, in variable speed units (either in pumping or turbine operation modes), the power response to the grid is mainly governed by the fast control action provided by the electronic power conversion stage rather than by the hydro mechanical system, as it is the case of fixed speed units [7]. The considered control structure for these models is described next, being developed in line with the aforementioned considerations for representing the man dynamics of systems involving power electronic conversion stages.

4.2.1. Synthetic Inertia (SI) provision model

The model presented in Figure 10 was designed for modelling the expected response of a variable speed unit following the provision of Synthetic Inertia (SI). In this model, it is assumed the SI functionality should be as much close as possible to the inherent synchronous inertia response of a synchronous machine, hence being proportional to the (filtered) time derivative of the grid frequency. In the model, a grid frequency deviation goes through a first order transfer function with a time constant (Td) that represents the filters delay and then multiplies by a derivative gain (Kd). Then, this response is derivated in time, inducing a response proportional to the Rate of Change of frequency, and is limited in terms of power output. This output is added to an active power setpoint, Pset, given by an external controller. This signal is then limited in terms of its Rate of Change and goes through a first order transfer function with a time constant (Tf) that represents the power converters time delay. The output signal is the converter electrical active power time response.

This model assumes that SI is provided independently of the remaining ancillary services, meaning that Pset must be the unit active power before the triggering of the SI service.

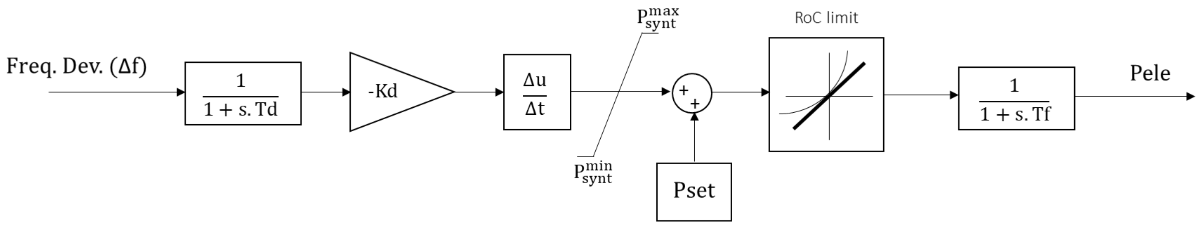

Figure 10 – Variable speed technology control structure for SI provision

The input signals are:

- Pset – active power setpoint (p.u.);
- Δf – grid frequency deviation from setpoint, given by fgrid - fset (p.u.).

The output signal is:

- Pele – electrical active power (p.u.).

The model's parameters are:

- Td – filter time constant for SI (s);
- Kd – derivative gain (p.u.);
- P_{synt}^{max} – SI maximum limit (p.u.) ;
- P_{synt}^{min} – SI minimum limit (p.u.);
- RoC limit – Rate of Change limit (p.u./s);
- Tf – converters delay time constant (s);

4.2.2. Fast Frequency Response (FFR) provision model

This model, which is presented in Figure 11, was tuned for the provision of Fast Frequency Response. A grid frequency deviation that goes beyond the frequency deviation threshold (FT) triggers an active power time response with a shape characterized by a FFR amount, a full activation time (ta), support duration time (Tdur), a ramp up time (tup) and a ramp down time (tdown). Then, the obtained power response is added to an active power setpoint, Pset, given by an external controller. This signal goes through a third order transfer function, which was found to be necessary to obtain a proper representation of the electrical active power time response at the converter output (the output signal).

This model assumes that FFR is provided independently of the remaining ancillary services, meaning that Pset must be the unit active power before the triggering of the FFR service.

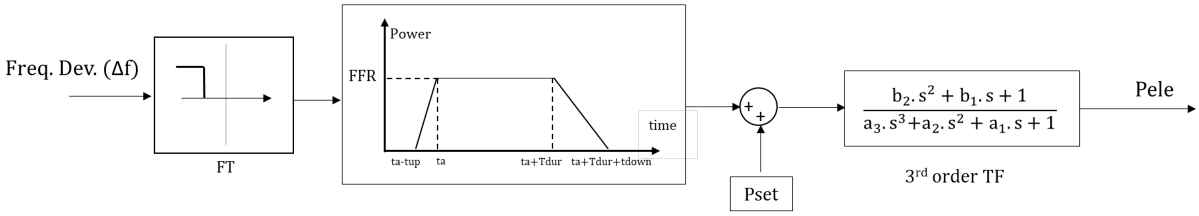

Figure 11 – Variable speed technology control structure for FFR provision

The input signals are:

- Pset – active power setpoint (p.u.);
- Δf – grid frequency deviation from setpoint, given by fgrid – fset (p.u.).

The output signal is:

- Pele – electrical active power (p.u.).

The model's parameters are:

- FT – frequency deviation threshold (p.u.);
- FFR – FFR capacity (p.u.);
- ta – full activation time (s);
- Tdur – support duration time (s);
- a1, a2, a3, b1, b2 – 3rd order transfer function parameters;
- tup – Ramp up time (s);
- tdown – Ramp down time (s).

4.2.3. FCR and aFRR provision model

The considered variable speed model for FCR and aFRR provision is presented in Figure 12. This model is similar to the one used for the provision of SI with an additional branch representing a speed droop control, comprising a first order transfer function with time constant Tp, a gain 1/Rp and upper/lower power limits. The signal from the speed droop control sums with the signal from SI and with an external active power setpoint, Pset. The obtained signal is then limited in terms of its Rate of Change and goes through a first order transfer function with a time constant, Tf, to represent the converters time delay. The output signal is the converter electrical active power time response.

If only providing FCR, the power setpoint must be the unit active power before the triggering of the FCR service. The aFRR control comes through the Pset signal.

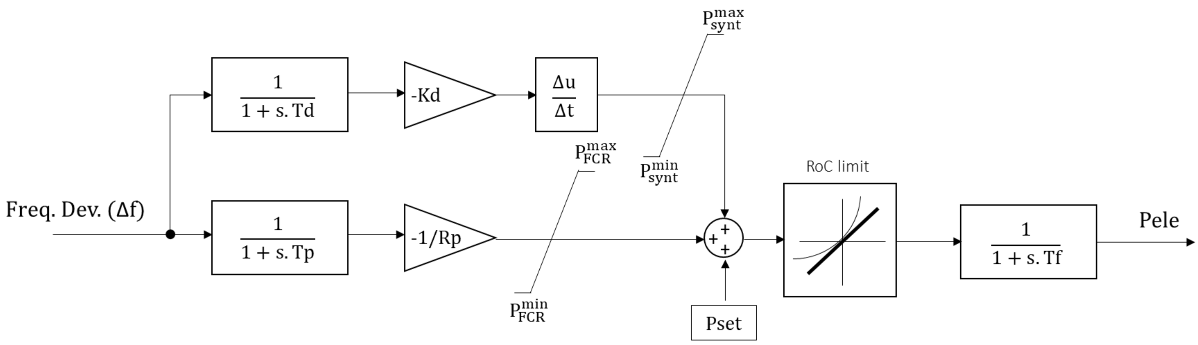

Figure 12 – Variable speed technology control structure for FCR and aFRR provision

The input signals are:

- Pset – active power setpoint (p.u.);
- Δf – grid frequency deviation from setpoint, given by fgrid - fset (p.u.).

The output signal is:

- Pele – electrical active power (p.u.).

The model's parameters are:

- Kd – derivative gain (p.u.);
- Td – filter time constant for SI (s);
- P_{synt}^{max} – SI maximum limit;
- P_{synt}^{min} – SI minimum limit;
- Rp – permanent droop (p.u.);
- Tp – filter time constant for FCR (s);
- P_{FCR}^{max} – FCR maximum limit (p.u.);
- P_{FCR}^{min} – FCR minimum limit (p.u.);
- RoC limit – Rate of Change limit (p.u./s);
- Tf – converters delay time constant (s).

5. Summary list with model's documentation

The list (on the XFLEX HYDRO website - here) summarizes the information regarding the set of models developed for each demonstrator with the technologies assumed to be implemented/tested for the provision of the selected ancillary services. To access each model documentation, the user just needs to click in the corresponding hyperlink of the list ("Click for model") pointing to a .pdf document describing the model. The model documentation is structured as follows:

- Block diagram of the model;
- List of model's inputs, outputs and parameters;
- Considered input signals for assessing each ancillary service/technology response;
- Model's time domain response, according to the considered input signals, and comparison with the reference time domain response provided by the detailed model simulations performed in task 2.3.

References

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