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Integration of Variable Speed Pumped Hydro Storage in Automatic Generation Control Systems

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Abstract. Pumped storage power (PSP) plants are expected to be an important player in modern electrical power systems when dealing with increasing shares of new renewable energies (NRE) such as solar or wind power. The massive penetration of NRE and consequent replacement of conventional synchronous units will significantly affect the controllability of the system. In order to evaluate the capability of variable speed PSP plants participation in the frequency restoration reserve (FRR) provision, taking into account the expected performance in terms of improved ramp response capability, a comparison with conventional hydro units is presented. In order to address this issue, a three area test network was considered, as well as the corresponding automatic generation control (AGC) systems, being responsible for re-dispatching the generation units to re-establish power interchange between areas as well as the system nominal frequency. The main issue under analysis in this paper is related to the benefits of the fast response of variable speed PSP with respect to its capability of providing fast power balancing in a control area.

1. Introduction

The growing integration of new renewable energy (NRE) sources such as wind and solar power has driven electrical power systems to adapt to a new operational paradigm. Although their acknowledged advantages, generation from NRE induce high levels of uncertainty and variability in the system when compared to the conventional technologies (e.g., coal-fired thermal plants, combined and open cycle gas turbines as well as hydro power plants). To overcome these major drawbacks, energy storage devices have been referred as a possible solution that is able to leverage high levels of NRE deployment throughout worlds' electrical power systems [1]. Particularly, along with these are the pumped storage power (PSP) plants, which explore the possibility of using reversible units, able to either generate power or to pump water to an upstream reservoir. PSP plants have proved to be the most utilized, mature, efficient and cost-effective technology for large-scale energy storage, and may be playing an important role in handling the NRE integration issues in the future by providing storage capacity and advanced system support function in the form of fast ramps for power balancing purposes [2]. Thus, alongside a worldwide effort for energy decarbonisation, a commercial and technical interest for these (and other types of storage) units has been renewed.

The need for generation units' increased operational flexibility has driven the exploitation of new power generation solutions within the hydropower context by exploring variable-speed machines. The controllability provided by converter-connected units enables faster power-to-grid responses through the exploitation of higher ranges of turbines' speed and respective kinetic energy stored in its rotating masses, since the generator rotational speed is decoupled from the grid frequency.

However, the massive integration of NRE and subsequent replacement of conventional machines have significant impacts on the frequency control robustness either due to the enormous reduction of the system inertia as well as because of the reduction of the number of fully controllable units connected to the grid. In order to provide grid frequency control services, generation units are required to provide



enough power reserves. As soon as a disturbance in the grid occurs, frequency containment reserve (FCR) is provided automatically and locally by some generation units, assuring excursions are contained and rapidly stabilized. Afterwards, the provision of frequency restoration reserve (FRR) which is activated centrally by the system operators through automatic generation control (AGC) systems is responsible for re-establishment of the nominal system frequency and the power interchanges between the so-called control areas.

In line with this control organization in electric power systems, this paper presents and discusses the role of a variable speed hydro PSP plant in the regulation mechanism supported by the AGC system. Taking into account the controllability characteristics of the variable speed units, it is demonstrated its effectiveness in the provision of fast responses for an improved power balance in a given control area in both the pumping and generation modes. The improved power balance capabilities that can be achieved with variable speed units are compared with those provided by a conventional synchronous-based machine. Besides the importance of validating the integration of such units in the AGC system, this work intends to highlight the advantages of using variable-speed units, interfaced with the grid through power converters, when dealing with FRR provision in order to re-establish frequency and inter-areas power flow to the pre-defined values.

2. Pumped storage power (PSP) plants

From a technological perspective, PSP plants store energy using the height difference between the headwater and tailwater reservoirs. The main operation principle of PSP is storing water during periods of low demand and releasing it during periods of high demand. These plants are typically highly efficient (>80%) and have been proving to be very beneficial in providing load balancing services to the electric power systems, while also allowing its promoters to obtain commercial profits from these temporal arbitrage energy management activities [3]. Despite the aforementioned benefits, an important drawback of the existing PSP schemes is the prominent use of fixed-speed pump-turbines. Although the traditional fixed-speed design has worked well for many decades, there are limitations to its performance which are becoming apparent as power system requirements are changing in view of the increasing penetration of NRE. In response to these limitations, variable-speed machines integration in hydropower plants is a new technology being now exploited. Recognizing that hydropower is the most mature and controllable renewable based energy source currently available, it is undertaking profound technical developments such that it becomes more effective to support the sound integration of NRE, based on its intrinsic high regulation and storage capabilities. Current advanced designs for PSP plants lay on the use of electronic converters that act as the interface with the grid as well as perform the machine's control, using technologies as the doubly-fed induction machines (DFIM) and, yet in a less extend, synchronous machines connected to the grid through full-scale frequency converters (FSFC). In all the cases, the use of power electronic interfaces allows for the pump turbine rotation speed to be controlled, offering improved flexibility in the amount of power that can be absorbed in pumping mode. Moreover, the variable speed technology enables to operate Francis pump-turbines in pumping mode with extended head operating range, offering the possibility to cover the entire head range of PSP subjected to large head variations. Additionally, and regarding the turbine operation mode, this enables a PSP plant to operate at higher efficiency over a larger portion of its operating range, also contributing for the enhancement of the integration of renewables. In the same perspective, the ability to provide frequency regulation services is also considerably enhanced due to smoother operation at partial load conditions and the ability for fast power adjustment [4]–[6].

To study the performance of a variable-speed PSP unit and its benefits when integrated in AGC systems, thus allowing its active participation in the FRR provision, a reduced-order model of a Francis turbine connected to a DFIM was used. In order to perform system stability studies, coping with limited computational effort, a reduced detail modelling approach was used. Since modelling process is out of the scope of this paper, detailed information about the PSP unit modelling deduction, structure and respective validation can be found in [7]. Generally, the adopted model tackles both operation modes – turbine and pumping – which are addressed separately. As it can be understood in the aforementioned reference, hydropower units allow the modelling decoupling of both the hydro-mechanical and the electro-mechanical parts. In the case of the turbine mode, the representation of the hydraulic system was

based on the non-ideal turbine general expression given in [8], which relates gate opening and mechanical power variations around a given operating point. Contrary to what happens in the turbine mode, when the machine is working as a pump, the influence of the gate opening in the system operation is not significant. For that reason, an alternative model that explores an electrical analogy to relate hydraulic components was used. Details about the hydraulic model for pumping mode can also be found in [6]. A phasor modelling approach is used to represent the DFIM. The electric machine is represented by a transient model based on a voltage source being a transit reactance, being the mechanical part represented by a single-mass model (rigid shaft).

3. Automatic generation control (AGC)

Most synchronously-interconnected electric power systems are nowadays regulated by automatic systems that are responsible to maintain a stable and steady operation, including technical and economic considerations. In general, system operators (SO) have the responsibility for maintaining target values of grid frequency and scheduled tie-lines power flows, thus requiring the exploitation of FRR [9]. This type of action is automatically assured by each control area transmission system operators (TSO) through an AGC system, responsible to re-dispatch committed generation units within each load-frequency control (LFC) area.

For illustration purposes the block diagram of Figure 1 depicts the overall organization of an AGC system for a control area with two generation units.

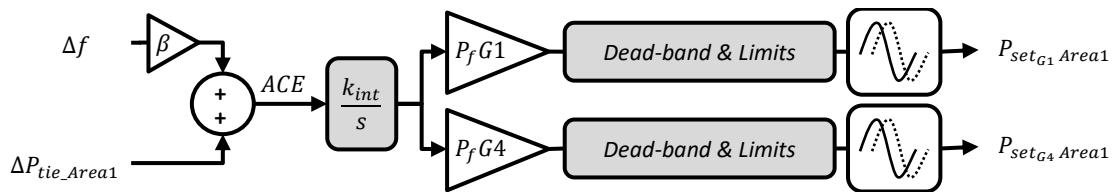


Figure 1. Area 1 detailed view of the control architecture.

For a given control area m , as the frequency deviation (Δf) and the power deviation in the tie-lines ($\Delta P_{tie\ Area_m}$) with respect to the pre-scheduled value changes, in the moments subsequent to a disturbance affecting the generation and load balance, the AGC is set to respond automatically by sending new active power set-points for the n generation units ($P_{set_{G_n\ Area_m}}$) under its control responsibility. Depending on the magnitude of the disturbance, the FRR needed from each generator is defined as a function of the area control error (ACE). This value adds in a linear combination of the Δf , which is affected by the stiffness ($\beta_m = \frac{1}{R_n} + D_m$, given in p.u./Hz, where R_n is the power speed droop of generator n and D_m is the load damping coefficient [10]), and the $\Delta P_{tie\ Area_m}$. The ACE is then fed to an integral controller (k_{int} gain in Figure 1) that computes the total amount of FRR required to cancel the ACE error and therefore assure frequency recovery to the nominal value as well as the re-establishment of the tie-line programmed flows. Based on the output of the integral controller, participation factors ($P_f G_n$) are used to define the power set-point to be assigned to each generator.

4. Test case definition

This section summarizes the simulation conditions used to study the behaviour and the benefits of including a hydro PSP plant in the AGC scheme, where it actively participates in the provision of FRR. The network and respective models were developed and implemented in the simulation platform MATLAB/Simulink®.

4.1. Network

A three-area network test system (depicted in Figure 2) was used in the performed simulation studies. This network comprises three main voltage levels: 21,6kV for the generation systems, being the transmission grid established at high and extra-high voltage levels of 230kV and 500kV respectively. It is assumed that generator G3 (located in control area 3) consists of a hydro PSP while all the other generators are referred to thermal units using synchronous machines. A brief summary of the network's

operational conditions can be consulted in Table 1 and Table 2. It was considered that power flowing between areas is defined to be positive when power is being extracted from a given area. Therefore, the tie-lines powers, in the same tables, are presented with the negative signal. The same occurs for the hydro PSP plant: positive active power means the unit is generating power while the negative signal indicates it is consuming power, while working in pumping mode. For the purpose of implementing the AGC system for each of the control areas, inter-area tie-line power flows are related according to the following equations (a) and b):

$$a) \quad \begin{cases} \Delta P_{tieArea1} = \Delta P_{tie12} - \Delta P_{tie31} \\ \Delta P_{tieArea2} = \Delta P_{tie23} - \Delta P_{tie12} \\ \Delta P_{tieArea3} = \Delta P_{tie31} - \Delta P_{tie23} \end{cases} \quad b) \quad \begin{cases} \Delta P_{tie12} = P_{tie12} - P_{tie12_{ref}} \\ \Delta P_{tie23} = P_{tie23} - P_{tie23_{ref}} \\ \Delta P_{tie31} = P_{tie31} - P_{tie31_{ref}} \end{cases}$$

The power flow in the three transmission lines connecting area 1 and area 2 are used to define P_{tie12} , being its respective scheduled reference value $P_{tie12_{ref}}$. In the same way, the power flow in the four transmission lines connecting area 2 and area 3 are used to define P_{tie23} (its reference represented by $P_{tie23_{ref}}$). Areas 1 and 3 are not directly connected so P_{tie31} is only defined (and its reference value $P_{tie31_{ref}}$) to facilitate the mathematical comprehension. Its values are therefore considered to be null.

Table 1. Network power summary.

	Area 1		Area 2		Area 3	
Load Power (MW)	500		1200		1500	
	G1	G4	G2a	G2b	G3	G5
Rated power (MW)	1000	130	900	900	±750	900
Init. Power (Turbine) (MW)	616.5	82.5	572.5	572.5	600	567.5
Init. Power (Pumping) (MW)	830	117	814	814	-375	810

Table 2. Inter-area ref. power.

Tie-line reference power		
Turbine mode	Pumping mode	
-225	-472	$P_{tie12_{ref}}$
-250	-984	$P_{tie23_{ref}}$
0	0	$P_{tie31_{ref}}$

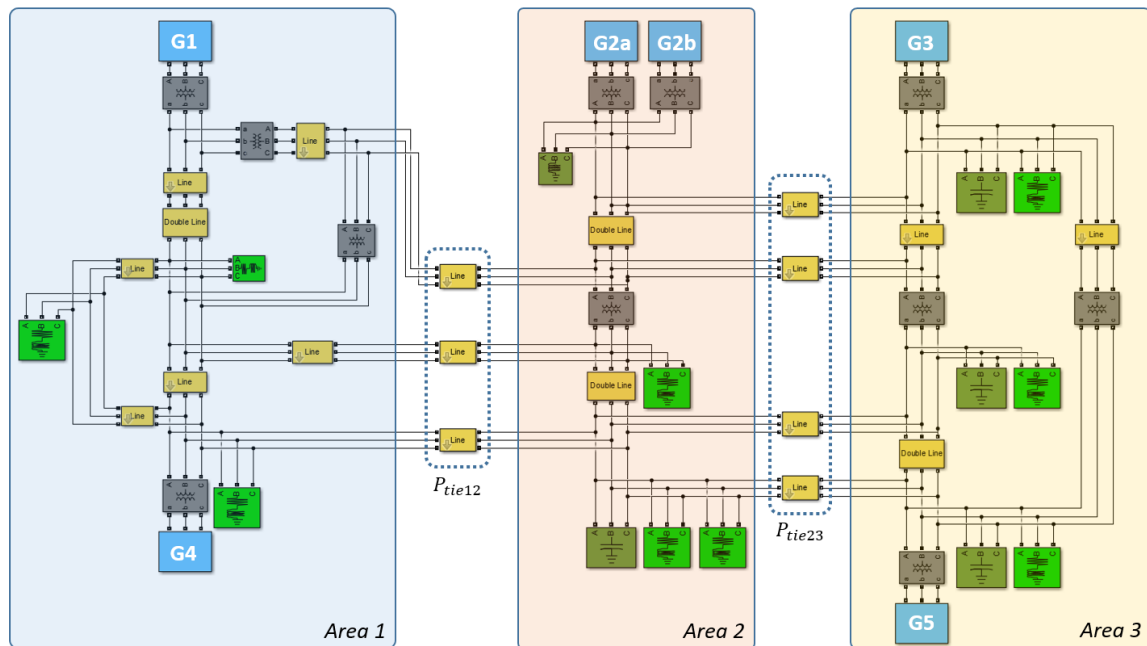


Figure 2. Three-areas network used in the simulation platform.

The main parameters used in the simulation studies regarding the AGC system are summarized in Table 3.

Table 3. AGC simulation parameters.

	Area 1		Area 2		Area 3	
Parameters	G1	G4	G2a	G2b	G3	G5
Droop (R)	0.05	0.05	0.05	0.05	0.05	0.05
Participation factor (P_f)	50%	50%	50%	50%	100%	0%
Damping (D)	0.05		0.05		0.06	
Integral gain (k_i)	-0.03		-0.03		-0.09	

4.2. Test cases

To study the response of the hydro PSP plant within the AGC scheme, three main tests were performed and are presented in this paper. A 50 MW load increase in Area 3 (where the hydro PSP plant is located) was simulated considering two the PSP plant to be operating according to the following conditions:

- **Turbine mode:** conventional synchronous-based hydro unit performance was compared to a variable-speed unit using a DFIM.
- **Pumping mode:** variable speed unit using DFIM and controlled by power converters.

The comparison, in turbine mode, between the fixed and variable speed units allow to demonstrate the advantages of using fast-responses units in the participation of FRR within the AGC scheme. Alongside, and once the reversible characteristic of the PSP plants is one of the main services these units can provide, contributing hence for NRE integration, the pumping mode is included.

5. Simulation results

Regarding turbine operation mode, the tie-lines power flow (Figure 3) re-establishment in the moments subsequent to the disturbance occurred in Area 3 is significantly faster when using a variable-speed PSP unit when compared to a PSP with a synchronous generator. Its controllability and improved power-frequency response characteristics leads to a faster tracking capability of the AGC control signal and consequently to a faster response when analysing the re-establishment of tie-line flows. To support this power-to-grid response, as it can be observed in Figure 4, the unit takes advantage of the wider range of available turbine speed. When the load increase occurs the power converters respond almost immediately (constrained by the ramping limits defined in order to impose a limit on the power converters dimension, set within the turbine speed deviation reference of $\pm 7\%$ of its nominal speed) and the speed deviation around the nominal value tends to be much larger. Additionally, the frequency recovery occurs also faster for the variable-speed unit due to the same reasons.

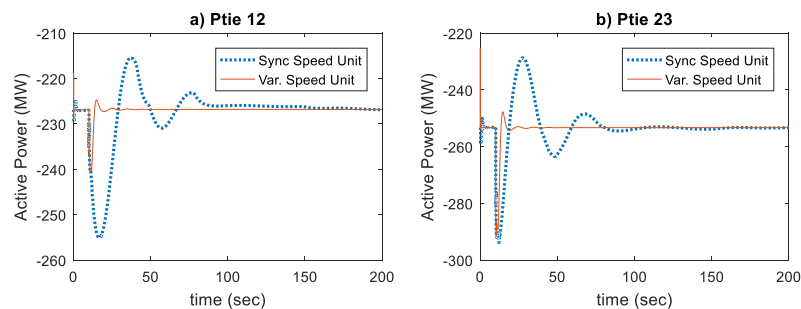


Figure 3. Turbine mode: Tie-lines power flow compared responses to 50MW load increase in Area 3, for synchronous and variable-speed hydro PSP plant.

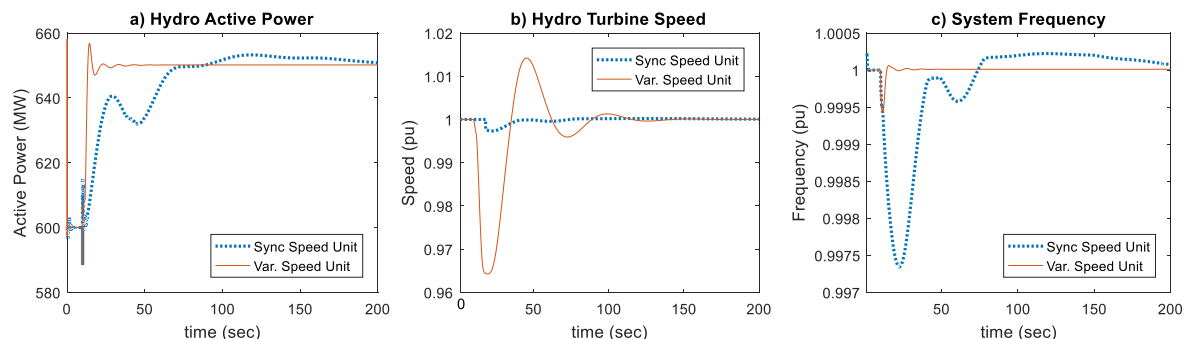


Figure 4. Turbine mode: Synchronous and variable speed hydro PSP plant response to 50MW load increase in Area 3.

Regarding pumping mode operation (Figure 5), the behaviour of the hydro unit and the impact of its response regarding FRR provision is similar to turbine mode operation. Both tie-line power flows are

re-established considerably fast – within around 40 seconds – as occurred when working as a generator, due to its fast power-to-grid response.

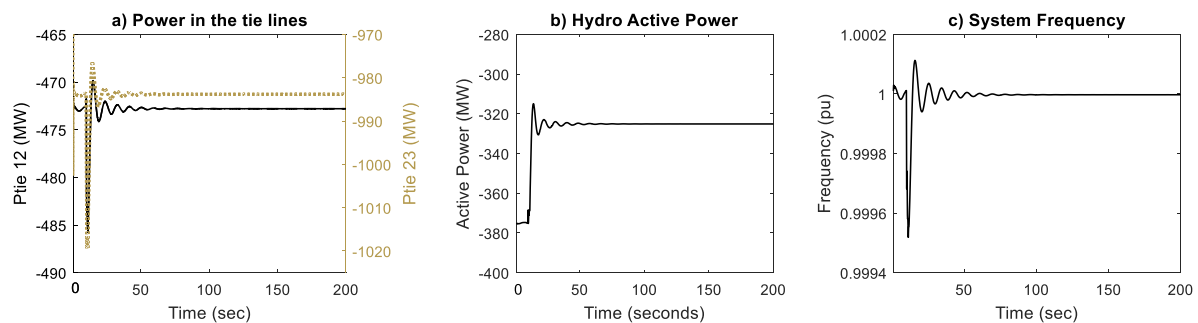


Figure 5. Pumping mode: Hydro PSP plant response to 50MW load increase in Area 3.

6. Conclusions

The need for new and better strategies that support the increasing growth of new renewable energies (NRE) is deploying a progressive interest in new forms of large-scale energy storage devices. Along with this, hydro power plants, due to its mature and highly efficient technologies are raising a renewed interest, especially when offering the possibility of working with reversible characteristics enabling pumping operation mode. Pumped storage power (PSP) plants are expected to play an important role when dealing with NRE integration by accommodating some of its uncertainty and variability. However, the replacement of conventional synchronous units for NRE – which normally rely on power-electronics connections to the grid – significantly decreases the system inertia and, hence, the robustness of frequency control. In order to understand how can PSP plants participate in the frequency restoration reserve (FRR) provision, a three-areas network controlled by an automatic generation control (AGC) system, responsible for re-dispatching units for FRR provision, was implemented and tested in this paper. Due to its electrical characteristics, these units have proven to be much faster, when compared to conventional hydro units – synchronous machines based – responding very much positively to disturbances and in the provision of FRR. Their power converters controlled connection, which allow a more flexible operation, have also proven to be rather advantageous when dealing with fast set-point changes, hence contributing to a better performance of the AGC and the overall system. Such conclusions demonstrated variable speed PSP ability to provide key system balancing functionalities in scenarios with high shares of NRE.

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