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Role of pump hydro in electric power systems

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Abstract. This paper provides an overview of the expected role that variable speed hydro power plants can have in future electric power systems characterized by a massive integration of highly variable sources. Therefore, it is discussed the development of a methodology for optimising the operation of hydropower plants under increasing contribution from new renewable energy sources, addressing the participation of a hydropower plant with variable speed pumping in reserve markets. Complementarily, it is also discussed the active role variable speed generators can have in the provision of advanced frequency regulation services.

1. Introduction

Energy storage devices in general and pumped storage power (PSP) plants in particular play an important role for handling new renewable energy (NRE) sources (such as solar and wind) variability and uncertainty[1]-[3]. In what concerns associated capacity, PSP plants are the sole technology that nowadays can effectively face the challenges of variability resulting from a large share of NRE integration. In a large number of existing studies addressing energy storage alternatives for future electric power systems, PSP is found to be the most mature, efficient and cost-effective technology [4]-[5]. For example, the available PSP capacity in Germany (currently at 7.6 GW) is projected to increase by up to 60% until 2020 [6]. Other studies have shown similar significant potential in the United States [7]. A whole-system approach of potential storage solutions in Great Britain has demonstrated that beyond NRE accommodation, large-scale storage schemes entail a number of additional system-wide benefits, such as reduction of required investment in generation, transmission and distribution assets [8]. Currently, exist 270 PSP stations around the world (fully operational and under construction) with a combined capacity of 120 GW. The vast majority of existing hydro power plants employs a conventional setup based on reversible single-stage Francis pump-turbines [9]-[10]. An important drawback of the existing schemes is the prominent use of fixed-speed pump-turbines. Although the traditional fixed-speed design has demonstrated good performance during many decades, there are significant limitations that are becoming apparent as power system requirements are changing while facing the increasing penetration of NRE. The conventional design's main limitations are related to the inability to adjust the pumping input power and the fact that the unit cannot operate over the whole turbine operating range. These limitations significantly reduce the ability for PSP plants to have a more important contribution in order to balance the rapidly-varying output of NRE and to provide ancillary services, especially when pump operating mode is in cause.

The intrinsic variability and uncertainty of NRE create several challenges in power system operation and planning. In every instant, generation must follow load variations in order to maintain the generation-load balance. The highly variable nature of NRE (e.g., rapid generation ramps) represents a

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challenge, in particular for systems without hydropower, since it introduces variations in the generation-side that can only be smoothed within the physical constraints of the conventional power plants (e.g., ramping up and down, minimum generation limits). In general, the available ramping rates of flexible generation units and fast-starting units (e.g., hydropower) are used for accommodating this variability. If these new type of solutions are not adopted, variability and uncertainty of NRE could lead to situations with high operational cost. For instance, the curtailment of renewable generation during low load periods and the start-up of expensive fast-starting units lead to a cost increase. Moreover, even with perfect forecast for the next hours/days, it is necessary to have in the system flexible generation units for accommodating the generation ramps.

Aiming to provide additional flexibility in electric power systems with high share of NRE, variable-speed hydro machines are a technological option that was firstly deployed in Japan and later in Europe. Nowadays, two main technological solutions can be identified: the use of variable speed technology through the installation of a doubly-fed induction machine (DFIM) or the use of a synchronous generator connected to the grid through a full size frequency converter (FSFC). Worldwide, there are a total of 36 variable-speed PSP plants projects: 17 projects with a total installed capacity of 3.6 GW are operational and 19 projects with a total capacity of 4.6 GW are under construction [10]. In Europe, the main variable-speed operating units are installed in Goldisthal (Germany) with 1060 MW being half of its capacity equipped with variable speed technology, Grimsel II (Switzerland) with 400 MW comprising 100 MW variable speed units equipped with FSFC, Avče (Slovenia) with 185 MW, Nant de Drance and Linth-Limmern with respectively 900 MW and 1000 MW (Switzerland) and Venda Nova III (Portugal) with 736 MW (under final construction phase).

The increasing penetration levels of NRE into electric power grids, together with its specific energy converters technological characteristics, led system operators (SO) to define very restrict rules (grid codes) for allowing increasing NRE penetrations. In general, present grid codes require different generation sources to withstand several disturbances and to support network stability through the provision of ancillary services similarly to those provided by conventional synchronous units. Recalling for international grid code requirements for wind power integration into electric power systems, they can be generally organized in five main categories: (a) fault ride-through requirements, (b) active and reactive power responses following disturbances, (c) extended variation range for the voltage–frequency, (d) synthetic inertia, active power control or frequency regulation support, and (e) reactive power control or voltage regulation capability. Taking the envelop of these requirements and the specific case of hydro power technology, the controllability offered by variable speed units makes possible to provide enhance flexibility for improving global system operation by providing important contributions with respect to system requirements.

2. Participation of Variable Speed PSP in the Electricity Market

Compared to conventional fixed-speed PSP, which in general participate in electrical energy sessions (i.e., day-ahead, intraday) and replacement reserve (RR), variable-speed PSP presents a flexibility band that makes it an important asset for frequency restoration reserve (FRR). This reserve category is generally remunerated with a capacity (€/MW) and electrical energy price (€/MWh), which makes it attractive from the financial point of view. Therefore, it is necessary to develop advanced optimization algorithms for the identification of the best opportunities for the participation of variable-speed PSP units in reserve markets, as well as to deal with wind power variability and uncertainty.

As a first step, a survey of the electricity market rules was conducted to study the international rules for FRR and RR. It was identified that the current fast dynamic automatic generation control (AGC) in place at several U.S.A. system operators might be beneficial for PSP units and it is important to study the economic gains of this new AGC signal. Moreover, most of the markets have a capacity price for the FRR (see [11] for a complete overview). Afterwards, an optimization problem for the operation of hydropower plants under increasing contribution from new renewable energy, addressing the participation of a hydropower plant with variable speed PSP in the FRR and RR markets, was developed.

The optimization problem is formulated for determining the reserve capacity bids for each hour of the next day.

A second optimization problem is also formulated, and covers a future scenario where wind power plants participate in the electricity market. In this case, an electrical utility, with hydropower and wind power in its portfolio, combines both generation sources to mitigate wind power forecast errors and try to maximize the income from selling FRR capacity [12]. A stochastic optimization problem, including wind power forecast uncertainty, is developed to compute the market bids (energy and reserve) of this virtual power plant (VPP) for the next day.

2.1. Individual Participation of Hydropower Plants

The accurate economic evaluation of variable-speed PSP in the electricity market requires a mathematical model for its flexibility band, suitable to be integrated in the formulation of optimization problems [13]-[14]. This mathematical model was embedded in a chain of optimization models depicted in Figure 1. The framework is divided in the following blocks:

- *Data analytics*: bootstrapping and forecasting algorithms employed to generate long-term and short-term input data related to market prices (electrical energy and reserve) and natural water inflows.
- *Medium-term optimization*: takes into account the seasonality and variability of the natural water inflows combined with market prices to find the optimal allocation of the water resource for one year, considering weekly periods (i.e., 52 weeks) (adapted from [16]). In order words, this module defines the initial and final levels of the water reservoirs for each week.
- *Short-term optimization*: aims to maximize the revenue of the system for a period of one week, considering two different sources of income, the day-ahead electrical energy market and the FRR market (which is also dispatched for the next day).
- *Evaluation module*: evaluates the performance of the bidding strategy, where the markets offers determined by the optimization problem are applied to real market conditions. The real prices are used to evaluate the economic gains, as well as realized natural water inflows.

The final outcome is the market revenue obtained by the hydropower plants from the participation in the electrical energy and reserve market sessions. The results are presented in a complement paper [17] and showed that by having a variable speed pump unit the system revenue increased by 12% in comparison with a fixed speed.

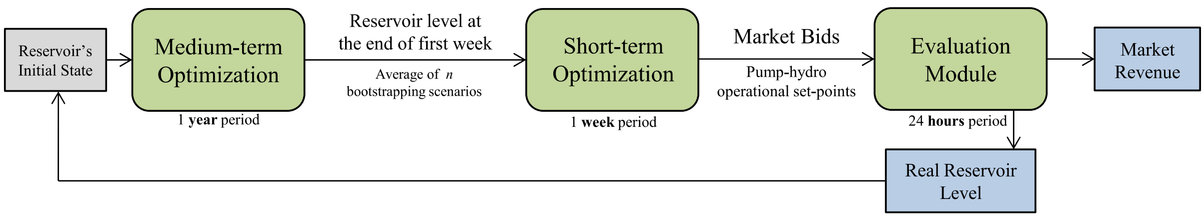

Figure 1. Optimization framework of a variable speed hydropower plant participating in the electricity market.

2.2. Hydropower Plants Combined with Wind Power Plants

In order to analyze the economic gains of combining variable speed hydropower and wind power plants, the framework depicted in Figure 2 was implemented.

In this framework, the PSP flexibility (i.e., between min and max values) is divide into three categories: (i) capacity margin to handle wind power variability; (ii) capacity margin to mitigate wind power uncertainty (forecast errors); (iii) upward and downward FRR capacity band around the offer presented to the day-ahead electrical energy market.

Using a machine learning algorithm (gradient boosting tree), a probabilistic forecast is generated for the maximum difference between min and max wind power generation levels within a hourly period (captures variability) and for the wind power generation level (captures uncertainty). The first probabilistic forecasts is an input to define the variability capacity margin, which guarantees a flat generation profile of the hydro-wind VPP (as depicted in Figure 2). The second probabilistic forecast is used to define the capacity margin to mitigate wind power forecast errors, which results in a minimization of the imbalances costs from the wind power plant.

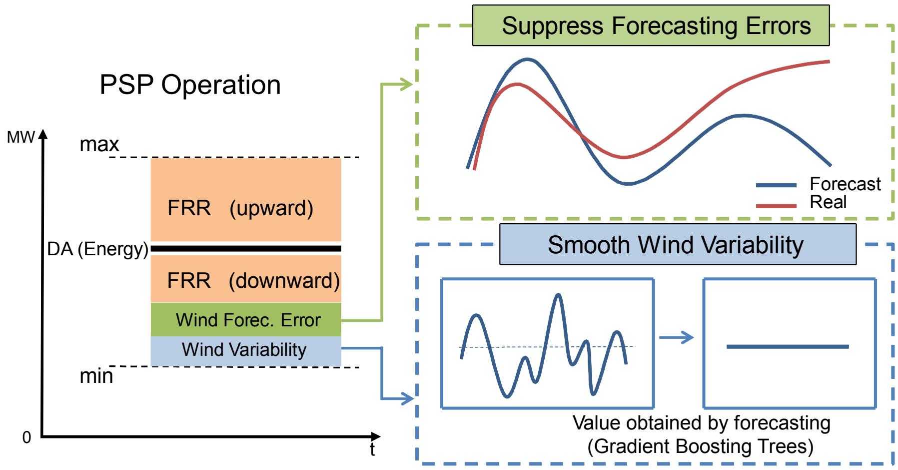

Figure 2. Joint optimization strategy for the combination of a variable speed hydropower and wind power plants.

After estimating these capacity margins, an optimization problem is formulated to determine the optimal offers for electrical energy and FRR capacity from the VPP. An evaluation module was also developed to estimate the economic gains considering the realized prices and natural water inflows. Figure 3 illustrates the hydro and wind power operating curves for a scenario where the FRR price is greater than the electrical energy prices.

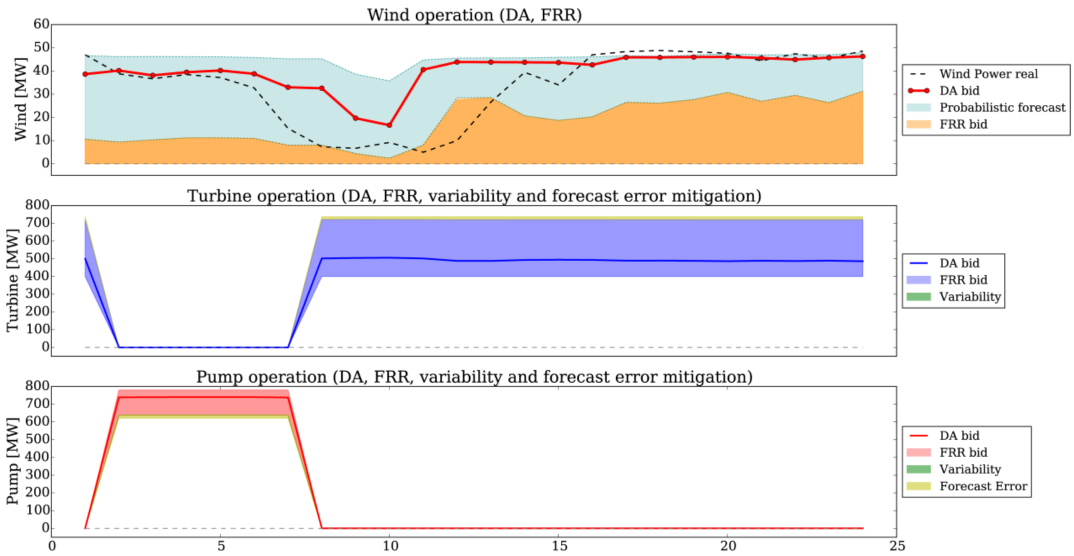

Figure 3. Operating curves for scenario where FRR price is greater than electrical energy prices.

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Obtained results showed that there is an added value, both technical and economically, on coordinating the wind farm with a PSP unit with variable speed pumping capabilities. From an economic point of view, the added remuneration comes from the provision of FRR by the wind farm without the need of operating throttled (the Portuguese TSO mandates that 2/3 of the FRR band must be for upward regulation). Furthermore, the PSP unit is able to smooth the wind power variability and mitigate forecasting errors that, otherwise, would lead to market penalties.

3. Provision of Frequency Regulation Services from Variable Speed Hydro Units

Electrical power systems and their control are facing a continuous transformation process as a result of large scale integration of NRE. Nowadays, the grid control services are largely based on large-scale power plants with classical synchronous generators. In the future grid scenario of up to 100% shares of renewables, the active contribution of inverter-based generators to the grid stability and to the security of power supply becomes absolutely necessary. In this view, the flexibility of hydropower is, in one hand, an expected key contribution, and in the other hand an additional difficulty, as in many cases the desired enhanced flexibility range is itself achieved with inverter based generators. Therefore, new services are required like fast frequency containment reserve (FCR) or provision of synthetic inertia in order to meet stable network operation conditions in case of critical disturbances.

The provision of this type of system services (FCR and the provision of synthetic inertia) in variable speed hydro units can largely benefit from the controllability that is offered form inverter-based generators used in both FSFC and DFIM technologies. In this technologies, the use of inverter-based generator allows that in both the turbine and pump modes, the active power output of the machine can be directly controlled by the power electronic interface. Consequently, the fast control action of the power electronic interface makes possible to achieve the desired modulation of the active power output of the unit through the use of a local frequency controller, as it is depicted in Figure 4 and Figure 5. Regarding the turbine operation mode, when a power set-point change is requested to the PSP plant, (for example, resulting from the action of the frequency controller as a result of the speed-droop) it can be directly used at the machine power converters in order to control the active power output. At the same time, the power set-point can be used at the "speed optimizer" in order to define the best efficiency speed reference at which the machine should operate. As a result of a change in the machine's power output, the unit's speed varies as well, being then regulated by the speed governor. Regarding the pump operating mode, it is well known that gate opening control only slightly influences the efficiency of the PSP plant. Therefore, the control strategy of the unit consists on the active power control through the VSC converters, being the speed defined through the characteristic curves of the unit.

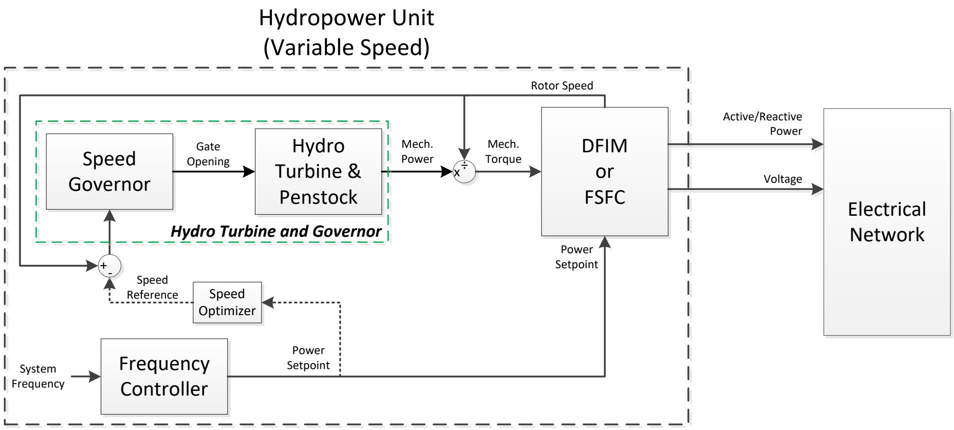

Figure 4. Functional block diagram of power generation and control system for a variable speed PSP plant.

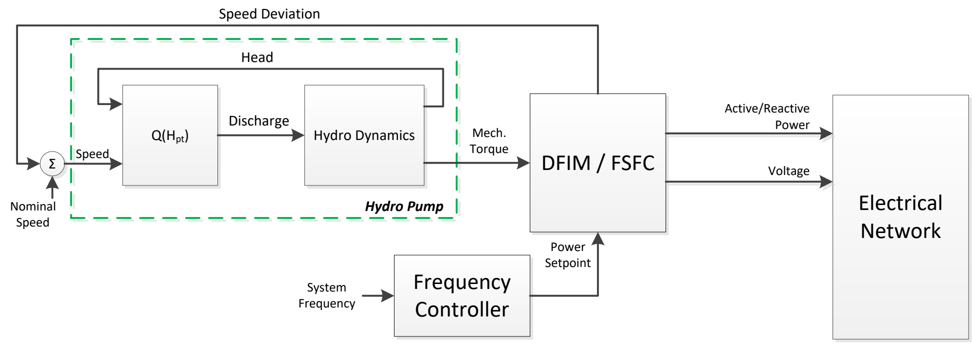

Figure 5. Functional block diagram of a variable speed hydro unit in pumping mode.

In both pumping and turbine operating modes, the frequency is responsible for modulating the unit active power response with respect to grid frequency changes. Therefore, it can incorporate the conventional active power/frequency speed-droop based controlled for the provision of FCR as well as dedicated controllers for the provision of synthetic inertia, for example by modulating the output power proportionally to the rate of change of the grid frequency. As an example, Figure 6 illustrates the response of a variable speed unit in comparison to the response of a classic synchronous-based hydro generator.

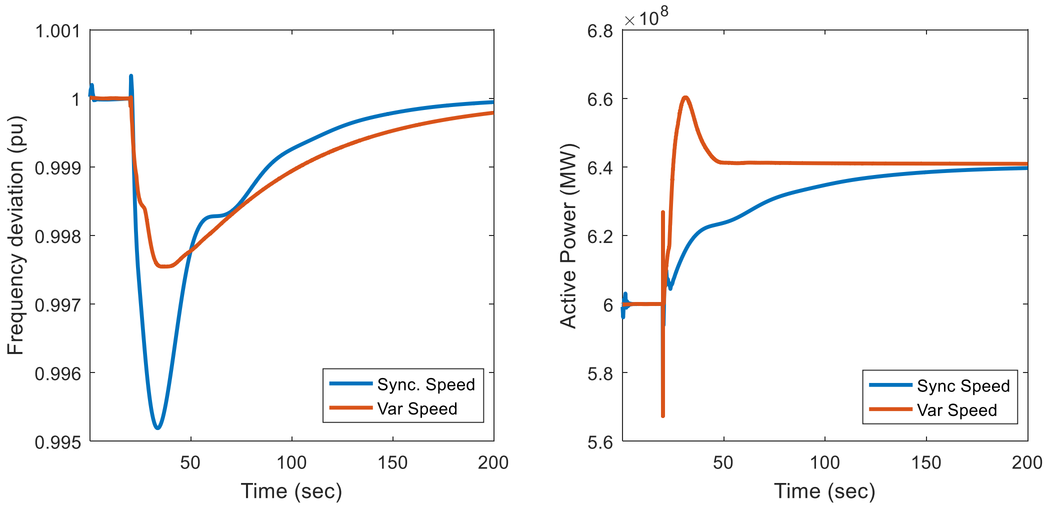

Figure 6. Functional block diagram of a variable speed hydro unit in pumping mode.

4. Final Remarks

Hydropower constitutes nowadays a mature technology that can actively contribute to leverage a sound integration of NRE. The controllability and flexibility characteristics of variable speed generators are of utmost importance regarding the need of providing advanced system support functions in scenarios with massive integration of NRE. In fact, the large scale integration of NRE introduces new challenges associated to the variability and uncertainty of these sources that require specific mitigation strategies. Energy storage capability is one possible mitigation strategy that can be conveniently exploited from hydropower making it by far one of the most effective resources to provide the necessary flexibility and controllability for managing future electricity supply/demand challenges. At the same time, the controllability provided by inverter-based generators applied in variable speed hydro units provides increased performance with respect to provided enhanced frequency regulation services for securing grid operation in future electric power systems.

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