Journal of Physics: Conference Series

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IOP Conf. Series: Journal of Physics: Conf. Series **813** (2017) 012010 doi:10.1088/1742-6596/813/1/012010

On the Profitability of Variable Speed Pump-Storage-Power in Frequency Restoration Reserve

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Abstract. The increase penetration of renewable energy sources (RES) into the European power system has introduced a significant amount of variability and uncertainty in the generation profiles raising the needs for ancillary services as well as other tools like demand response, improved generation forecasting techniques and changes to the market design. While RES is able to replace energy produced by the traditional centralized generation, it cannot displace its capacity in terms of ancillary services provided. Therefore, centralized generation capacity must be retained to perform this function leading to over-capacity issues and underutilisation of the assets. Large-scale reversible hydro power plants represent the majority of the storage solution installed in the power system. This technology comes with high investments costs, hence the constant search for methods to increase and diversify the sources of revenue. Traditional fixed speed pump storage units typically operate in the day-ahead market to perform price arbitrage and, in some specific cases, provide downward replacement reserve (RR). Variable speed pump storage can not only participate in RR but also contribute to FRR, given their ability to control its operating point in pumping mode. This work does an extended analysis of a complete bidding strategy for Pumped Storage Power, enhancing the economic advantages of variable speed pump units in comparison with fixed ones.

1. Introduction

Reversible hydro power plants with reservoir (Pumped Storage Power - PSP) are the most mature storage technology with high integration levels in countries such as Portugal, Spain and Switzerland. Typically, the fixed speed PSP participate in the day-ahead (DA) electricity market for price arbitrage (i.e., pump in low price periods and generate in high price periods) and provision of downward replacement reserve (RR) in specific cases. Due to technical limitations, the current fixed speed PSP technology does not participate in the frequency restoration reserve (FRR). In contrast, variable speed PSP units can not only participate in RR but also in FRR, given their flexibility to quickly change the generating/consumption operating point.

Several works have begin to study the added value of variable speed PSP in the electrical grid in terms of network stability, but only few explore the market perspective. In [1] it is analysed the technical benefits achieved by replacing the existing fixed speed pump units by variable speed ones in an Indian PSP unit, leading to significant benefits since adds frequency regulation in a location where the nominal frequency is constantly below 50Hz. [2] and [3]

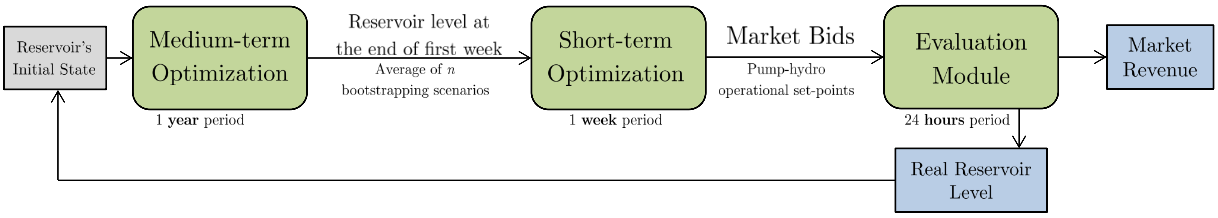


Figure 1: Architecture of the Optimization Framework

explore the use of a ternary unit operated in hydraulic short circuit to provide active power control in pumping mode and concludes that it improves the Virtual Power Plant output power and thus the power network frequency stability in case of significant solar power variations. In [4] it is presented an overview of the trends and challenges in PSP, which clearly states that ancillary services markets, particularly those related to balancing supply and demand, emerge as a valuable source of revenue.

To the authors knowledge, the recent work of [5] was the first to formulate an optimization problem for variable-speed PSP participation in the FRR market, which is then used to estimate the maximum theoretical revenue of the system. The work assumes perfect knowledge of market prices and water inflows and that the amount of energy to be used from the total reserve band available is known at the time of the optimization. In [6] a complete bidding strategy is presented where no prior knowledge of the market operation is assumed, all inputs are acquired through forecasting techniques, allowing its implementation in a real world scenario. The economic analysis was made between a PSP that participates only in the DA market and one that also bids in the FRR market.

In this paper it is presented an extended analysis of the complete bidding strategy previously presented in [6] for operating a PSP unit in the day-ahead market, by performing price arbitrage, but also bidding in the ancillary services market. Compared to [6] the present paper has the following original contributions: a) the possibility to operate either with one or two groups of machines, b) representation of electrical and hydraulic losses in the I/O curves used and c) a fairer economic analysis, by comparing two PSP that bid in both DA and FRR markets, one with a fixed speed pump and the other variable.

2. Bidding Strategies Framework

In Figure 1 is depicted the overall bidding strategy framework for the participation of a PSP unit in the DA and FRR markets, which is divided into three modules: (i) a Medium-term Optimization where is performed an optimal allocation of the water that naturally flows into the reservoir; (ii) a Short-term Optimization that defines the PSP operational set points aiming to maximize its revenue, achieved by combining inputs originating from forecasting techniques (water inflows, DA and FRR market prices) with the technical characteristics of the pump-hydro unit; (iii) an Evaluation Module that, using realized data from the electricity market and water inflows, is able to emulate the PSP real operation and them calculate the actual revenue of the system. As it is clear from the interpretation of Figure 1, the strategy implementation is cyclical. After calculating the updated level in the reservoir, this value is then used as the initial state and the strategy restarts.

2.1. Medium-term Optimization Model

The operation of a PSP unit relies in the correct management of its only resource, i.e. water. The medium-term optimization model, inspired in the work of [7], uses the concept of water value by taking into account the seasonality of the natural water inflows combining it with weekly day-ahead market prices forecasts. Thus finding the optimal allocation of the water resource throughout the year, considering weekly periods (i.e., 52 weeks). The detailed description of this model can be found at [6].

2.2. Short-term Optimization

The short-term optimization is responsible to optimally define the operating set-points of the PSP, in other words, the moments where it will operate as pump or turbine and as well as the portion reserved to FRR provision. The formulation of this optimization model presumes that it is not possible to determine *a priori* the amount of electrical energy that will be activated used from the available reserve band. Thus, the revenue for the FRR is represented in the objective function only for the reserve capacity price. Following the same logic, the amount of reserve band made available to perform FRR does not affect the rate of discharge/pumping water flow or the amount of water available in the reservoir. To avoid situations where the energy used in the frequency restoration would result in the violation of a reservoir level it is assumed that a portion of the reservoir is allocated solely for the purpose of frequency restoration.

In order to define the set-points the algorithm relies on a set of forecasted data, such as DA and FRR market prices (π_{DA}, π_{FRR}) and natural water inflows, as well as the technical characteristics of the unit. The objective function (1) aims to maximize the revenue of the system in both markets, DA and FRR, for a period of one week ($t = 168$ hours).

$$\max \sum_{t=1}^{t=168} \Big[(g^d_{DA,t} - g^p_{DA,t}) \cdot \pi_{DA,t} + (us^d_t + us^p_t + ds^d_t + ds^p_t) \cdot \pi_{SEC,t} \Big] \tag{1}$$

Several constraints related with the technical boundaries of the machine as well as equality balance equations for the reservoir are imposed and exhaustively detailed in [6]. Furthermore it is also enforced the Portuguese transmission system operator (TSO) rule, which defines that the amount for upward secondary reserve must account for 2/3 of the total band, leaving 1/3 for downward regulation.

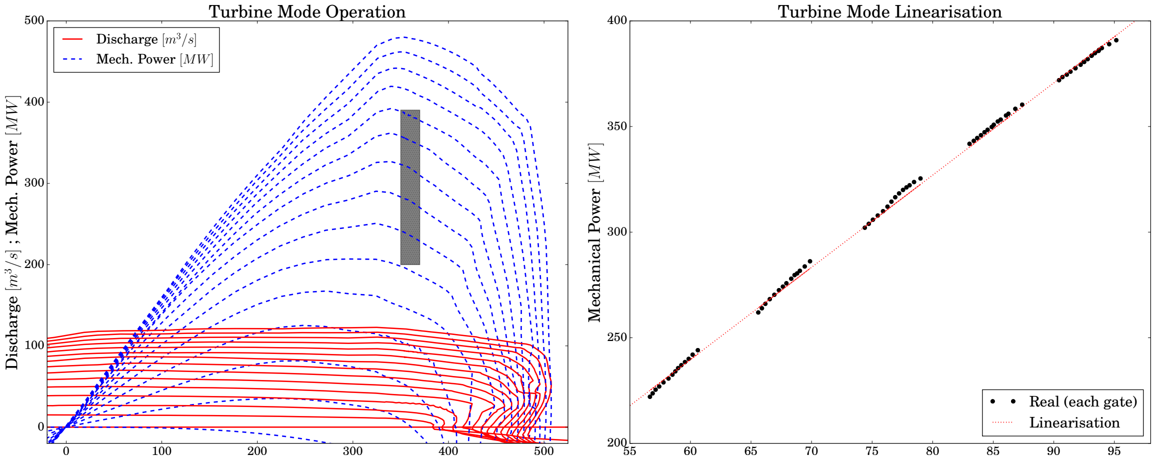
2.3. Evaluation Module

To assess the performance of the bidding strategy an evaluation module emulates the real operation, by applying the markets bids determined by the optimization problem to real market conditions. Observed prices from the electricity market are used to evaluate the economic performance and observed natural water inflows used to update reservoir level. Despite the weekly period of the short-term optimization model, the MIBEL only accepts bids for the day-ahead, so in this evaluation module only the first 24 hours bids are considered. Since FRR remuneration is made in two fractions, reserve band and energy activated, it is necessary to estimate the latest based on the ratio of the overall energy used and the total amount of FRR reserve contracted, detailed in (2) for the upward activation but the same method is applied to downward. The amount of energy used is also relevant to update the level of the reservoir, since, the use of the PSP unit to perform downward regulation results in more water stored in the reservoir.

$$\% \uparrow_t = \frac{\text{upward FRR energy used } (t)}{\text{upward FRR band contracted } (t)} \; (\%) \tag{2}$$

3. Case Study

To accurately represent the conversion between water flow and power, we applied a methodology adapted from [8] and [5] to the s-shape characteristic curves (normalized for the point of max efficiency and fixed head - Figure 2a) for all the gate openings, provided by the manufacture of the machine. These curves were affected by two quadratic curves in order to represent both the hydraulic and electrical losses of the system. By restricting the operation to the machine's



(a) (b)

Figure 2: Turbine mode: (a) Normalized s-shape curve (for max efficiency) (b) Linearization

technical limits (highlighted by the shaded rectangle) the outcome is a linearisation of said curves (Figure 2b) to be able to use them as input in a mixed integer linear optimization problem.

The bidding strategy was applied to a real PSP unit located in the north of Portugal, with two groups of machines, each with the ability to operate in turbine mode between 200MW and 390MW, and in pump mode between 300MW and 390MW. The reservoir has 15.8hm^3(92.1-76.3hm^3) of water available to for the PSP operation. Real data for the MIBEL market prices[1,2] and natural water inflows were also used. The period between Jan 2014 and Jan 2015 was considered.

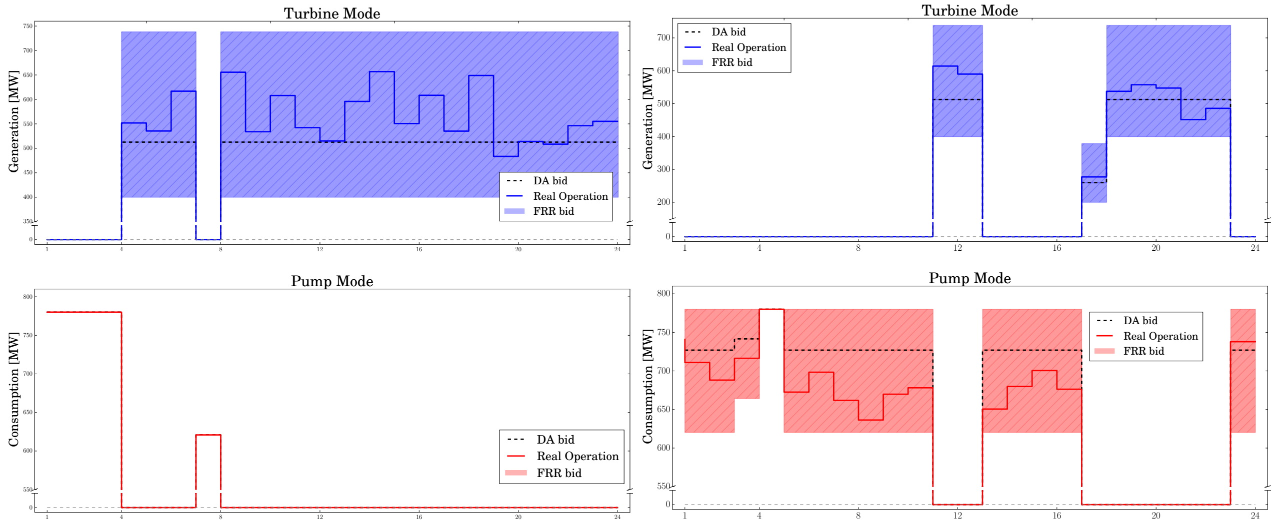
Figures 3a and 3b represent two typical optimization days, the former considering a PSP with fixed speed pump unit while the last regards an identical PSP but with variable speed pumping capabilities. The dotted lines correspond to the day-ahead market bids and the shaded area to the FRR reserve band, both obtained by the short-term optimization. Bold lines represent the actual power generated or consumed by the PSP unit, being the difference between the DA bid and the actual power the activated energy for FRR provision. Analysing both figures, it is possible to observe that in some situations it is more profitable to operate with only one group of machines (hour 7 in F.3a and hour 18 in F.3b) instead of two. This is a consequence of the reservoir level constraint, either imposed by the medium-term optimization or by its physical limits. In some periods, due to the nature of the market prices, the bidding strategy favours the DA bid and opts by not providing FRR (hour 5 in F.3b) or reducing its offer (hour 4 in F.3b).

An economic analysis was made by comparing the revenues of variable speed PSP with a fixed one, as well as comparing the operation with just one group of machines versus two groups, in the Iberian Market environment. Results are described in Table 1 and Figure 4a.

As expected, with variable speed PSP the revenue from the day-ahead market suffers a small decrease, but it is largely compensated by the revenue from the FRR market. The overall revenue of a PSP with variable speed achieves an increase of 12% in comparison with a fixed one. Additionally we can observe that doubling the amount of machines does not guarantee a proportional gain in terms of revenue, predominantly due to the limited size of the reservoir.

Since the amount of energy used from the reserve band was not considered in the short-term optimization model, it is possible that during the operating day the reservoir level could be

[1] www.mercado.ren.pt
[2] www.esios.ree.es



(a) (b)

Figure 3: DA and FRR bids considering a PSP with fixed speed (a) and variable speed (b) pumping capabilities

Table 1: System Revenue from DA and FRR, considering pumping with variable and fixed speed

	Single Group Mach.		2 Groups Mach.		
	Fixed Speed	Variable Speed	Fixed Speed	Variable Speed	
Day-ahead	33.10	31.34	40.28	36.27	(EUR 10^6)
Frequency R. R.	37.45	44.01	63.68	80.03	(EUR 10^6)
Total	70.55	75.35	103.96	116.3	(EUR 10^6)

above or below its technical limits. Furthermore, forecasting errors on the natural water inflows could also result in discrepancies between expected and real amount of water stored. Figure 4b shows a histogram of the difference between the actual level after the operation and the amount of water expected after the optimization process. As depicted, in this case study, rarely the real reservoir level is greater than the expected, while the opposite is frequent. However, during all the simulation, only 1.9% of the hours the real reservoir level was above its technical limit, registering an absolute minimum level of 74.83hm^3. This deviation indicates that if we increase the minimum reservoir level by 1.5hm^3, it is expected that the technical constraints would not be violated.

4. Conclusion

In [6] was demonstrated the validity of the bidding strategy as well as the economic benefit of adding the FRR to the PSP market portfolio. In this paper the same strategy was applied with two added features: representation of losses, both hydraulic and electrical, and the possibility to operate with one or two groups of machines.

It was shown that a PSP with a variable pump unit could increase its revenue by 12% in comparison with a fixed unit. Furthermore, the amount of groups of machines does not led to a proportional gain in revenue, since it is constraint by the stasis of the storage capacity. It was also concluded that the consequences arising by discrepancy between expected and real reservoir level could be mitigated by increasing the reservoir's minimum level constraint by 1.5hm^3.

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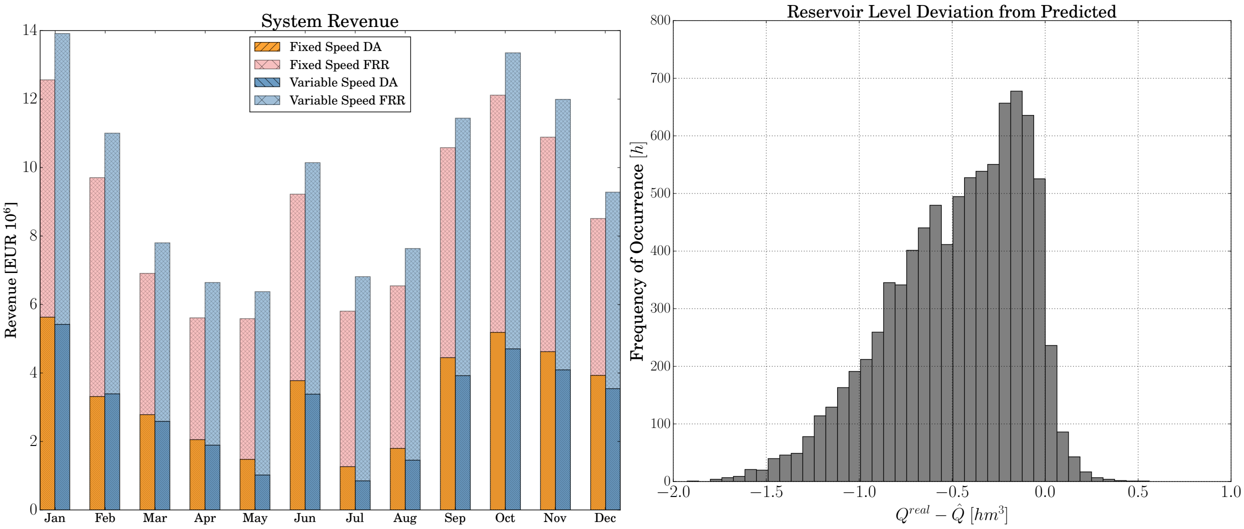

(a) (b)

Figure 4: (a) System Revenue from DA and FRR, considering variable and fixed speed and (b) Reservoir level deviation from the predicted

Acknowledgments
The authors graciously thank the partners from the FP7 European Project HYPERBOLE for the valuable comments about the pumped storage power modelling and EDP Produção for the provision of technical data and natural water inflow time series. A special mention to Christophe Nicolet from Power Vision Engineering for the contribution in modelling the I/O curves and Jiri Koutnik from Voith for providing the s-shape curve.

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