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Impact of a price-maker pumped storage hydro unit on the integration of wind energy in power systems

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A B S T R A C T

The increasing integration of larger amounts of wind energy into power systems raises important operational issues, such as the balance between power generation and demand. The pumped storage hydro (PSH) units are one possible solution to mitigate this problem, once they can store the excess of energy in the periods of higher generation and lower demand. However, the behavior of a PSH unit may differ considerably from the expected in terms of wind power integration when it operates in a liberalized electricity market under a price-maker context. In this regard, this paper models and computes the optimal PSH weekly scheduling in a price-taker and price-maker scenarios, either when the PSH unit operates in standalone and integrated in a portfolio of other generation assets. Results show that the price-maker standalone PSH will integrate less wind power in comparison with the price-taker situation. Moreover, when the PSH unit is integrated in a portfolio with a base load power plant, the role of the price elasticity of demand may completely change the operational profile of the PSH unit.

1. Introduction

Wind power has grown considerably worldwide in the last two decades, with a global installed capacity rising from 6 GW, in 1996, to 318 GW, in 2013 [1]. As wind power varies its availability over different timescales, the integration of larger amounts of wind into the power systems raises important technical challenges [2]. Among these is the imbalance between generation and demand, which is increasingly important in periods of low demand and high wind availability, resulting in the potential occurrence of over-generation [3].

Considering the high efficiency of the pumping cycle and its storage capacity, the pumped storage hydro (PSH) units are increasingly seen as a solution to integrate the over-generation, avoiding the need for wind power curtailments [4–6]. This interaction between wind power and PSH units is relevant in countries with a high share of wind power, such as Portugal [3,7], Ireland [8,9] and Denmark [10], as well as in many other countries around the world [11–16].

This solution assumes that the PSH units have the incentive to store the over-generation in the most beneficial way to the power system, condition that is met in a centralized dispatch context. However, when trading in a liberalized electricity market, the PSH unit will pursue a profit maximization strategy, purchasing electricity for pumping and selling its generation in the day-ahead electricity market when profitable [17–19].

Considering the PSH unit as a price-taker [20], in periods with low demand and high wind generation, which drive market prices down, there is an incentive for the PSH unit to pump water, leading to an adequate integration of wind power.

However, when a PSH unit is a price-maker [21–23] and operates in standalone mode, its profit maximization strategy leads to a decrease of storage levels and, therefore, the capacity to integrate wind power would be considerably reduced, as shown in Ref. [24].

Moreover, the PSH unit may be integrated in a generation company (GenCo) that has a generation portfolio with different power technologies. In this perspective, the PSH unit can behave strategically [25,26] to influence the market clearing price (MCP) in order to increase the revenue obtained by the power plants in the portfolio. In this context, the behavior of the PSH is not straightforward because the drivers of the PSH scheduling are more complex.

Regarding the study of the optimal PSH unit operation strategy in liberalized markets there is some relevant research performed by

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several authors. This is the case of [17] that developed an algorithm to determine the optimal bidding strategy for the day-ahead and ancillary services markets.

In addition to the day-ahead and ancillary services markets, Ref [27] also takes into account bilateral contracts in order to reach the bidding strategies that maximize the profit.

Considering the impact of market power in the behavior of a generation unit, several authors have developed methodologies to compute a strategy that optimizes its operation, such as [21], in a deterministic context, and [22,28,29], using a stochastic approach. Also, with the objective of maximizing the yearly profit, Ref [23] considers the impact of the market power, through a residual inverse demand function for yearly profit maximization, considering a deterministic first stage of one month and a stochastic approach for the other months.

In order to evaluate how the behavior of a PSH unit may differ from the power system objective of integrating wind power, this paper models a PSH unit and computes the optimal weekly scheduling in a price-taker and price-maker scenarios, when the PSH unit operates standalone and integrated in a GenCo with a portfolio of generation assets.

For this purpose, simulations were carried out using real data from the Iberian Electricity Market (MIBEL) for the price-maker situation, in order to compare with the price-taker outcomes. The effect of the PSH unit operation on the MCP was modeled by a residual inverse demand function with a variable elasticity that depends on the slopes of the demand and supply curves.

In the price-maker assumption, the inclusion of the PSH unit in a portfolio was pursued for 4 scenarios with different capacities of the base load thermal power plant: 500, 1000, 1500 and 2000 MW. The non-linear PSH profit optimization problem, subject to technical constraints, was solved using the MINOS solver of the GAMS programming language.

The paper is organized as follows. Section 2 presents the analysis of the day-ahead electricity market MCP, the mathematical formulation of the PSH profit maximization and the solution methodology to solve the PSH scheduling problem. Section 3 presents and discusses the results related to the scenarios simulated. Conclusions are drawn in Section 4.

2. Methodology

2.1. Market clearing price

In most of the day-ahead electricity markets, such as the MIBEL, market participants submit hourly electricity supply offers and demand bids for the entire following day.

For each hour of the day, the supply curve is built upon the supply offers, sorted by increasing offered prices, and the demand curve is built upon the demand bids, sorted by decreasing bided prices.

As an example, Fig. 1 illustrates the supply and demand curves of 1 h of the MIBEL day-ahead electricity market.

The last dispatched offer block sets the MCP for that hour, which takes into account the intersection of the supply curve (*S* line) with the demand curve (*D* line). It should be noted that there are complex offers that imposes constraints, which leads to some merit offers being disregarded when these conditions are not met. As a consequence of that, the supply curve shifts left, as represented by *S*′ line of Fig. 1. In this case, the market clearing quantity (MCQ) and MCP are set at E_0 and π_0, respectively, as shown in Fig. 1.

2.1.1. Effect of the PSH unit operation on the MCP

Under a double-sided auction mechanism, as is the case of MIBEL, buyers and sellers submit their competitive bids and offers

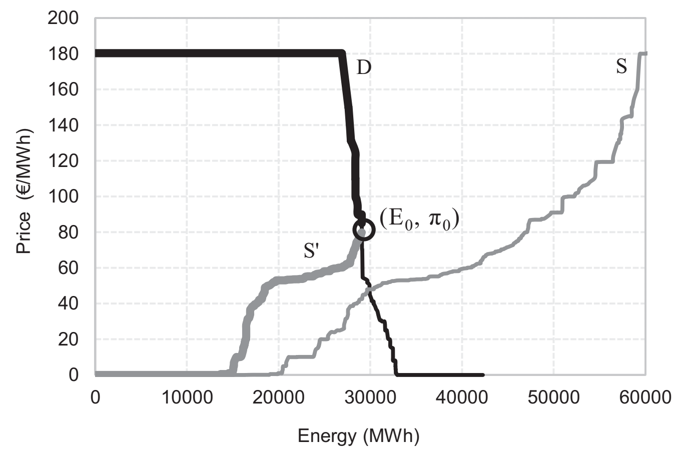

Fig. 1. Supply offers (*S* and *S*′) and demand bids (D) of 1 h of the day-ahead electricity market of MIBEL.

to the day-ahead market. In this context, unlike other power plants, such as thermal, that just generate electricity, the PSH units also consume electricity to perform pumping.

Thus, the effect of the PSH unit can influence the MCP in two different ways. On one hand, when the PSH unit pumps, it submits purchase bids that shift the demand curve to the right, pushing the MCP up. On the other hand, when the PSH unit generates, it submits sale offers that shift the supply curve to the right, pushing the MCP down.

To illustrate this effect, consider Fig. 2a where the PSH unit makes a purchase bid of ΔE that shifts the demand curve (represented by *D* line) to the right, to the position represented by *D*′ line. With this action, the intersection of the demand curve with the supply curve (*S* line) takes place at a higher price point of $\Delta\pi$.

This change in price depends on the slope of the supply and the demand curves, given by γ and β respectively, as represented in Fig. 2b, which can be expressed in terms of the changes in quantities and prices, given by:

$$\tan\gamma = \frac{\Delta\pi}{\Delta E_1} \tag{1}$$

$$\tan\beta = \frac{\Delta\pi}{\Delta E_2} \tag{2}$$

$$\Delta E = \Delta E_1 + \Delta E_2 \tag{3}$$

Considering a generator convention, when the PSH unit pumps, the respective purchase bid energy will be considered negative, that is $\Delta E < 0$. Moreover, when the PSH unit generates, the

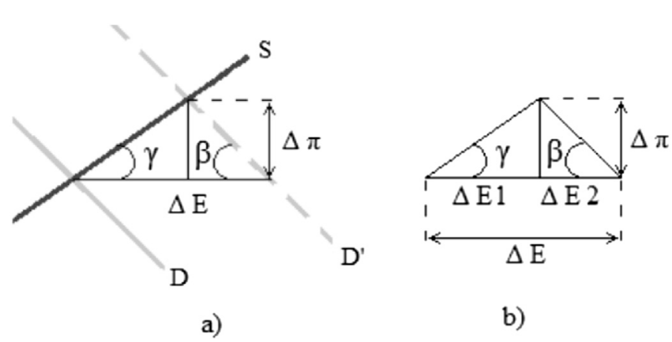

Fig. 2. Influence of the PSH unit operation on the MCP.