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Trends and challenges in the operation of pumped-storage hydropower plants

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ABSTRACT

The increasing penetration of renewable energy sources (RESs) in the power system has highlighted the benefits of being able to store energy in a more efficient manner, and the need of holding additional operating reserves to manage the system under more demanding conditions due to the inherent uncertainty and variability of wind and solar power. Pumped hydroelectric energy storage (PHES) is by far the most established technology for energy storage at a large-scale. PHES units have also participated in the active power-frequency control for years, and last technical developments in PHES have been oriented to improve their capability of providing regulation reserves by means of variable speed design or by hydraulic short-circuit configurations. This fact, together with the impact of RES on spot-market energy and ancillary services prices, is changing the operation and market conditions faced by PHES plants. The aim of this paper is to review the current trends in the PHES operation, to discuss why current practices should be re-examined, and to present the main challenges faced by PHES operators who will need to adapt their scheduling and bidding models to optimize jointly the operation in the energy and in the ancillary services markets.

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1. Introduction

Among the available technologies to store energy at a large-scale level, pumped hydroelectric energy storage (PHES) is the most widely adopted one. The big amount of potential energy that

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can be stored in hydro reservoirs, the energy conversion efficiency of the whole cycle, the cost per power unit, and the flexibility provided by these plants to the Transmission System Operator (TSO) in the short-term operation makes PHES the most attractive option for large-scale energy storage. As a consequence, pumped-storage hydropower plants (PSHPs) have been widely installed and operated since the 1890s, reaching an approximate worldwide installed capacity of 130 GW [1].

The traditional operation of PSHPs is mainly focused on satisfying the load by means of the so called hydro-thermal coordination. Thus, the water is pumped during off-peak hours when the demand is low, and it is released afterwards during peak-hours with an overall round-trip efficiency in the range of 70–80%. This cycle can be daily, weekly, or even seasonal when the plants are located in not-isolated hydro systems. In power systems organized as electricity markets, the operation of the generators depends on the results of the market clearing, and only an adequate pricing mechanism can lead to an optimal use of the generation resources.

Due to the well-known environmental concerns, and thanks to a number of different renewable energy sources (RESs) support policies [2,3], wind and solar power have increased notably their market share in many power systems during the last decade. Amongst all RESs, wind seems to be at present the one with the largest economically feasible potential [4], but also with the highest variability [5,6], and the most difficult to predict [7]. Therefore, the presence of high levels of wind power in the generation mix is challenging the operation of power systems. On the one hand, wind power inherent variability and uncertainty require more advanced scheduling models, having a direct impact on the amount and type of the required operation reserves [8]. On the other hand, both wind and solar power generators cannot decide to defer their generation as they are subject to the instantaneous meteorological conditions. Thus, RES curtailments can occur in case of having an excess of supply (particularly during off-peak hours) when conventional generators cannot reduce their output due to technical constraints. Increasing the storage capability, both at a local and at a system level, is a natural way to mitigate this problem [9,10].

Apart from the technical aspects, the increasing penetration of RES in power systems is also affecting the resulting spot-market prices. It has been reported that besides the impact on the average energy prices [11], RES can also affect the shape of the hourly price profiles [12]. As the profitability of the operation of PSHPs in a spot-market relies heavily on the relative difference between the electricity prices in off-peak hours (when the unit buys energy to pump the water from the lower to the upper reservoir), and in peak hours (when the units sell the energy generated by discharging the water from the upper to the lower reservoir), the change of the pattern of spot-market prices could have a remarkable economic impact. As a consequence, owners of PSHPs are looking for additional sources of revenues by increasing their presence in the provision of ancillary services.

The participation of PSHPs in the regulation reserve markets is not new. However, the last technical developments have been oriented to improve their capability of providing load-frequency control. In particular, special attention is given to variable speed PHES [13–15] and hydraulic short-circuit operation [5,16].

In this context, PHES “reemerges” as an excellent means to integrate wind power into the electric power system [17], not only because of its maturity and technically proven flexibility, but also because of its significant remaining potential [18–20]; and so it is demonstrated according to some recently projected values of PHES capacity in 2020 [21].

The objectives of this paper are (1) to review the current trends in the operation of PSHPs, (2) to discuss why current practices should be re-examined, (3) to check whether the existing models and approaches found in the literature are appropriate or not for an optimal planning and operation of PSHPs in the new framework, and (4) to present the main challenges faced by PSHPs owners who will need to adapt their scheduling and bidding models to optimize jointly the operation in the energy and in the ancillary services markets. It is important to note that the operation of small PHES facilities connected to local distribution grids, such as those integrated in irrigation or water supply networks, sometimes operating in coordination with small wind generators, is outside the scope of this paper. The reader interested in that type of PHES facilities is referred to [22–24].

This paper is organized as follows. Section 2 presents a review of current trends, where the discussion about their drawbacks to face the new framework is embedded in the different subsections. Section 3 presents the main challenges for the near future, and Section 4 summarizes the main conclusions of this work.

2. Trends of pumped-storage hydropower plants operation

The identified trends in the operation of PSHPs are presented in this section, divided according to four different subsections. In Section 2.1, main motivations for PSHPs operators to schedule the power generation and consumption of the PSHP considering its participation both in different energy and ancillary services markets are analyzed. Additionally, some relevant multi-market PSHP scheduling models are described. Section 2.2 focuses on how PSHPs operators cope with the different sources of uncertainty existing in liberalized market contexts, namely: the energy and ancillary services prices, the behavior of competitors in the diverse markets, the real time use of committed power reserves. Some discussions are included about the effect of the uncertainty on the fulfilment of longer term operation guidelines, such as target stored volumes at the end of the day or the week. In Section 2.3, the coordinated operation of wind and pumped-storage power plants is discussed, from the perspective of both the TSO and the PSHP operator. Section 2.4 deals with the operation of PSHPs capable to provide load-frequency control in pumping, or consumption mode, by means of variable speed or hydraulic short-circuit operation. Finally, in Section 2.5 main observed trends are summarized. Several comments have been included across Sections 2.1–2.4 in order to define the power scheduling models used in the cited papers, putting special emphasis on the optimization techniques used in the model, and other model features which are summarized in a table in Section 2.5. Additionally, some comments on which are the most widely used optimization techniques for short- and long-term power generation scheduling of PSHPs are included in different subsections.

2.1. Multi-market operation

Since the beginning of the nineties, power systems all over the world have gradually experienced a continuous process of deregulation. These new market schemes have served as a framework for the development of plenty of planning tools that assist the power generation companies to better utilize their energy resources.

As a result of the above-mentioned deregulation process, a wide number of electricity markets schemes have appeared all over the world. In spite of the differences among the distinct designs and rules of existing electricity markets, the activities of buying and selling electric power are in most cases organized around a short-term wholesale energy market. These markets are supervised by an independent agent usually referred to as the Market Operator, who is in charge of the market clearing process,