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Economic viability of pumped-storage power plants participating in the secondary regulation service☆

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HIGHLIGHTS

- The pumped-storage power plants are equipped with variable speed pump-turbine units.
- The pumped-storage power plants are operated in hydraulic short-circuit mode.
- The plants are proposed to participate also in the frequency regulation service.
- The variable-speed and the hydraulic short-circuit decrease the pay-back period.
- Plants with ternary units decrease the pay-back period with respect to binary units.

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ABSTRACT

This paper analyses the economic viability of twelve pumped-storage hydropower plants equipped with different fixed-speed and variable-speed units and with and without considering hydraulic short-circuit operation. The analysed plants are assumed to participate in the day-ahead energy market and in the secondary regulation service of the Iberian power system. A deterministic day-ahead energy and reserve scheduling model is used to estimate the maximum theoretical income of the plants assuming perfect information of the next day prices, the residual demand curves of the secondary regulation reserve market and the percentages of the real-time use of the committed reserves. An estimate of the minimum theoretical pay-back period is obtained from the maximum theoretical income as a result of the scheduling model. Results indicate that the economic viability with and without variable speed units and operating or not in hydraulic short-circuit mode is not discarded if the plants also participate in the secondary regulation service, and that the minimum theoretical pay-back periods can be reduced significantly when the plant is equipped with variable speed units and/or operates in hydraulic short-circuit mode. In addition, the maximum theoretical income obtained with the used optimization model and the proposed pumped-storage hydropower plants are significantly higher than the real income obtained by plants that are currently operating in the Iberian system.

1. Introduction

Pumped-storage hydropower plants (PSHPs) are considered worldwide as a mature technology to store large quantities of energy and to improve the flexibility of the power systems [1]. They are expected to play an important role in the context of a high penetration of intermittent renewable energies such as wind and solar power.

In this context, special attention is being given to the operation of PSHPs with variable speed and in hydraulic short-circuit mode [2]. However, there is, to the authors' knowledge, a lack of information in the technical literature about the economic viability of PSHPs operating with variable speed or in hydraulic short-circuit mode in comparison to conventional PSHPs.

The variable speed technology introduces several advantages in

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Nomenclature

B	binary units
BFF	fully fed frequency converter bypassed in generating mode
cSU^d	start-up cost in generating mode
cSU^p	start-up cost in pumping mode
DF	doubly fed frequency converter
DM	day-ahead energy market
ER2UP	income from the real-time use of the upward reserves
ER2DW	cost for the real-time use of the downward reserves
FF	fully fed frequency converter
FS	fixed speed
MTI	Maximum theoretical income
MTPB	minimum theoretical pay-back period
PSHP	Pumped-storage hydropower plant
RRC	Residual reserve curve, i.e. the residual demand curve of the secondary regulation reserve market
SC	hydraulic short-circuit operation
SM	secondary regulation reserve market
SRS	secondary regulation service
TF	ternary units with Francis turbines
TP	ternary units with Pelton turbines
TSO	transmission system operator
$\overline{v}$	storage capacity of the upper reservoir
VS	variable speed

conventional PSHPs (see [3] for more details): (1) higher hydraulic efficiency and wider operation range in generating and pumping modes, (2) ability to regulate power in pumping mode and (3) improvements in network stability [4]. Furthermore, the main advantage of the operation in hydraulic short-circuit mode is that the PSHP is able to regulate power in pumping mode, with a power regulation range equal to that of the turbines in operation (see [5] or [6] for more details).

The objective of this paper is to evaluate the economic viability of PSHPs equipped with different conventional fixed-speed and variable-speed units, with and without considering the operation in hydraulic short-circuit mode, participating in the day-ahead energy market (DM) and the secondary regulation service of the Spanish electric power system.

Several power plant configurations are considered in the paper as regards the type of hydraulic machine (Francis pump-turbine, ternary unit with Francis or Pelton turbine), electrical machine and grid connection (synchronous, synchronous with full converter bypassed or not in generating mode, doubly-fed induction machine), and whether or not the plant can operate in hydraulic short-circuit mode.

The economic viability is evaluated using the minimum theoretical pay-back period (MTPB), i.e. the minimum number of years in which the investment costs are expected to be recovered. The MTPB is estimated from the maximum theoretical income (MTI) and the investment costs of the PSHPs. The MTI is obtained from the results of a deterministic day-ahead energy and secondary regulation reserve hourly scheduling model, based on mixed integer quadratic programming (MIQP) that assumes a perfect knowledge of all uncertain variables involved in the problem, namely: energy prices, residual demand curves of the secondary regulation reserve market, percentage of the committed reserve requested in real-time by the Spanish TSO, and upward and downward secondary regulation energy prices. The model is sequentially run day by day for a time period of three years (2013–2015), using historical data. The investment costs of the PSHPs are estimated from available data in the technical literature of existing, to be commissioned and projected PSHPs. The MTPBs are estimated for twelve different PSHPs. All analysed PSHPs are considered to be of closed-loop and daily-cycle type. Most part of the technical data of the analysed PSHPs have been provided by General Electric (GE) Renewable Energy from some of its last prototypes or studies.

1.1. Literature review

Traditionally, PSHPs have been operated following a price arbitrage strategy, i.e. generating power during peak hours and consuming power during off-peak hours. The viability of conventional PSHPs with an operation strategy based on price arbitrage was profoundly studied in [7,8]. In the former, the authors obtain the MTI that a closed-loop and daily-cycle PSHP can obtain from price arbitrage in 14 different deregulated markets, considering different values of the operating hours. From the MTI, the authors determine the maximum rate of interest for a theoretical minimum level of investment to be profitable, as well as the maximum investment per unit of installed power that can be justified with a 10% rate of interest. The results obtained in the paper show that there is a significant variation in the potential for the investment in PSHPs across the analysed markets, and that in most analysed markets the price arbitrage is not a viable operation strategy. In [8], the authors estimate the MTI of a closed-loop and daily-cycle PSHP (with a 6-h charge/discharge cycle) in several deregulated electricity markets, considering different price arbitrage strategies. As in [7], the results obtained in [8] show that the MTI the PSHP can obtain from price arbitrage varies significantly from one electricity market to another, and that even assuming a low investment cost and a low rate of interest, the investment is not viable in most analysed markets.

Today, it is widely accepted that price arbitrage in the DM is not profitable for any storage technology in most deregulated electricity markets all over the world. Investors in energy storage attempt to make profit from other sources of revenue, such as balancing and regulation markets. As far as we know, the increase in revenue of a PSHP due to its participation in ancillary services was estimated for the first time in [9]. According to the results obtained in [9], a PSHP might almost double its daily revenue when it participates both in the DM and in ancillary services.

After [9], several articles have dealt with the profitability of pumped-storage and other storage technologies participating in the DM and/or diverse balancing and ancillary services markets. Such an operation strategy was referred to, in [10], as “cross-arbitrage”.

Ekman and Jensen [11] estimated the MTI of a generic energy storage system with a 70% round-trip efficiency that participates in the DM and some ancillary service markets in Denmark. The obtained MTI were then compared with the expenses for the considered energy storage systems, namely batteries, flow batteries and underground pumped-storage, concluding that only underground pumped-storage might be profitable as long as it participates both in the DM and the ancillary service markets. The profitability from the price arbitrage in the Danish DM turned out to be impossible regardless of the considered energy storage technology.

Walawalkar et al. [12] studied the economic viability of sodium sulphur (NaS) batteries and flywheel energy storage systems participating in the DM and regulation service of the NYISO (New York Independent System Operator), considering different values of the round-trip efficiency and the energy storage capacity, and three different regions within the New York State, each with similar on- and off-peak zonal prices. The authors of that paper analysed also the impact of the capital cost and round-trip efficiency on the cumulative probability distribution of the net present value (NPV), and found that both NaS batteries and flywheels had a high probability of positive NPV for both energy arbitrage and regulation, considering the market data in the period 2001–2005. Similar results can be found in [13] in the markets operated by PJM.