Optimal Joint Energy and Secondary Regulation Reserve Hourly Scheduling of Variable Speed Pumped Storage Hydropower Plants

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Abstract—This paper presents a mixed integer linear programming model for the hourly energy and secondary regulation reserve scheduling of a price-taker and closed-loop variable speed pumped-storage hydropower plant, considering the energy losses due to the use of electronic frequency converters. The plant participates in the day-ahead energy market and in the secondary regulation service of the Iberian electric power system. The model is utilised to compare the income of the plant with and without considering the variable speed technology, with synchronous or asynchronous machines, with and without bypassing the frequency converter in generating mode, and with and without perfect information of the electric power system data. Numerical testing results demonstrate that the operation with the variable speed technology could help notably to enlarge the income of the power plant and that the secondary regulation reserve market might be the main source of revenue for the power plant.


NOMENCLATURE

Superscripts

d, d′ Indicates that the magnitude is related to generation/discharge. The superscript d refers to pump-turbine units with variable speed (using a converter). When the superscript includes the prime symbol, i.e. d′, it refers to pump-turbine units with fixed speed (without using a converter).
p, p′ Indicates that the magnitude is related to consumption/pumping. The superscript p refers to pump-turbine units with variable speed (using a converter). When the superscript includes the prime symbol, i.e. p′, it refers to pump-turbine units with fixed speed (without using a converter).
s Indicates that the magnitude is related to the secondary regulation service (reserve or energy).

Sets

c Pump-turbine unit, running from 1 to C
k Discrete generation curves
n Price scenario of the day-ahead energy market and the secondary regulation reserve market
t Hourly period, running from 1 to T

Parameters

\( \beta \) Confidence interval
\( cSU_d \) Start-up cost in generating mode, €
\( cdSU_d \) Start-up cost in pumping mode, €
\( \delta^p_{c,k} \) Energy coefficient in generating mode, MW/Mm³/h
\( d\delta^p_{c,k} \) Energy coefficient in pumping mode, MW/Mm³/h
\( f \) Target water volume at the end of the last hour of the time horizon, Mm³
\( g^d_{c,k}, g^d_{c,k} \) Maximum and minimum technical power generation, MW
\( g^p_{c,k}, g^p_{c,k} \) Maximum and minimum technical power consumption of fixed speed pump-turbine units, MW. Note that the minimum technical power consumption equals the maximum as they operate with fixed speed.
\( H_{u}, H_i \) Gross head at the maximum efficiency and a head lower than \( H_u \), i.e. \( H_i < H_u \), m
\( l_t \) Time length of period t, 1 h
\( \lambda_{D,n,t} \) Day-ahead energy market price, €/MWh
\( \lambda_{S,n,t} \) Secondary regulation reserve market price, €/MW
\( \lambda_{up,t} \) Upward secondary regulation energy price, €/MWh
\( \lambda_{dw,t} \) Downward secondary regulation energy price, €/MWh
\( \mu \) Risk-averse weight factor, \( \mu \in [0,1] \)
\( \eta^d_{c,k}, \eta^d_{c,k} \) Efficiency at maximum and minimum water discharge, %
\( \eta^p_{c,k}, \eta^p_{c,k} \) Efficiency at maximum and minimum pumped water, %
\( \pi^d_{n}, \pi^d_{c,k}, \pi^d_{c,k} \) Probability of the price scenario
\( q^d_{c,k}, q^d_{c,k} \) Maximum and minimum technical water discharge of fixed speed pump-turbine units, Mm³/h
\( q^p_{c,k}, q^p_{c,k} \) Maximum and minimum technical water discharge of variable speed pump-turbine units, Mm³/h
\( q^p_{c,k}, q^p_{c,k} \) Maximum technical pumped water of fixed speed pump-turbine units, Mm³/h
\( q^p_{c,k} \) Maximum and minimum technical pumped water of variable speed pump-turbine units, Mm³/h

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I. INTRODUCTION

The hydropower sector is highly interested in both pumped storage hydropower plants (PSHPs) with variable-speed (VS) technology and PSHPs operated in hydraulic short-circuit mode as a means to increase their flexibility [1]. This paper is a complementary research of [2], where the authors presented a mixed integer linear programming (MILP) model for the hourly energy and reserve scheduling of a closed-loop and daily-cycle PSHP operating in hydraulic short-circuit mode. In the presented paper, we have tried to cover the remaining questions and challenges faced by the VS-PSHPs. In particular, given the variety of possible configurations (type of Hill diagram, type of converter, type of electric machine), this paper presents a generic mathematical formulation that can be used to assess the profitability of each configuration. Note that a VS-PSHP is equipped with variable speed drives whereas in a PSHP operating in hydraulic short-circuit mode the hydro units must operate at synchronous speed both in generating and pumping modes.

VS-PSHPs introduce several advantages when compared to fixed speed (FS) PSHPs (hereafter referred to as FS-PSHPs): 1) higher hydraulic efficiency and wider operation range in generating and pumping modes, 2) ability to regulate power even while in pumping mode and 3) improvements in network stability [3]. However, several factors can hinder the investment in this technology, such as: i) the income from the so-called price arbitrage strategy is not sufficient to recover the investment costs in several electric power systems, as studied in [4], ii) grid fees for transmission lines usage when PSHPs are consuming [5] or iii) water fees for utilising rivers or lakes [5].

In this context, the aim and contribution of this paper is twofold. Firstly, an MILP model for the joint energy and secondary regulation reserve hourly scheduling of a realistic closed-loop1 and daily-cycle VS-PSHP is presented. The model takes into account uncertainty in the day-ahead energy prices and in the secondary regulation reserve prices, and also the risk-aversion of the decision maker due to the uncertainty. Secondly, the paper quantifies the extent to which the VS technology with synchronous or asynchronous machines, with and without bypassing the frequency converter in generating mode and with and without perfect knowledge in the electric power system data is able to enlarge the income of a price-taker FS-PSHP that only participates in the day-ahead energy market of the Iberian electric power system (DM) or that in addition participates in the secondary regulation service (SRS) of the Spanish electric power system. The SRS in the Spanish electricity market comprises two concepts: 1) a day-ahead reserve market, which takes place after having cleared the DM and where power reserve availability is remunerated by the marginal market price, and 2) power reserve delivery in real-time, which is remunerated by the marginal price of the tertiary regulation market [6]. Note that the procedure for the procurement of secondary regulation is not exclusive of the Spanish system. For instance, a

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1Closed-loop PSHPs do not receive natural water inflows in the upper reservoir and do not release water from the lower reservoir
similar procedure is implemented in Norway, Sweden, Finland, Slovenia, Czech Republic and Romania in the short-term (less than a week) and in Denmark, Netherlands, Belgium, Germany, Austria and Switzerland in the long-term (more than a week) [7].

Diverse optimization models for bidding and/or scheduling FS-PSHPs in the day-ahead energy market [4], [8]-[10] and simultaneously in the energy and reserve markets [11]-[16] have been published in the literature. In addition to this, [17] presents a hydrothermal model with VS-PSHPs in the context of a centralised system, minimising the cost of the energy and frequency control reserves taking into account the transmission network. However, to the best of our knowledge, there are no papers (apart from [18], the early version of the presented paper) where the optimal scheduling of VS-PSHPs, participating in a liberalised system in the energy and secondary regulation reserve markets, has been explicitly formulated [1].

The proposed model, based on the one presented in [18], has been improved in order to also consider i) several units within the same PSHP, ii) the head dependency in the power generation, in the power consumption and in the available spinning reserve in generating and pumping modes, iii) the units’ start-up costs and decisions, iv) the remuneration of the real-time use of the reserves as a function of the hourly net energy (i.e., the upward minus the downward secondary regulation energy), v) that each reversible Francis pump-turbine unit is equipped by an electronic frequency converter, vi) to take into account uncertainty in the day-ahead energy prices and in the secondary regulation reserve prices, by means of a scenario-based approach and, finally, vii) the risk-aversion of the decision maker due to the uncertainty. In addition, the presented case study sheds some light on the profitability of the different proposed PSHP configurations and presents a comprehensive analysis that can help to identify the most appropriate ones, with and without assuming perfect knowledge in the prices.

The paper is organised as follows: Section II describes the variable speed technology and the benefits with respect to FS-PSHPs. Section III presents the model formulation. The application of the model to a realistic PSHP is presented in Section IV and finally, conclusions are described in Section V.

II. VARIABLE SPEED PUMPED STORAGE HYDROPOWER PLANTS

The first VS-PSHPs were commissioned at the beginning of the nineties of the past century in Japan [1]. Since then, the interest in VS-PSHPs has increased considerably: 1060 MW of VS-PSHPs were installed in the period 2000-2010 in Europe and another 4410 MW are planned in the period 2011-2020 [3].

Currently, there are two different types of pump-turbine units with VS: 1) the unit is equipped with a synchronous machine and a converter between the stator and the grid [19] or 2) the unit is equipped with a doubly-fed induction machine and a converter between the rotor and the grid [20]. The converter rating in the former case is the same as the machine rating, introducing higher costs and power losses. Therefore, this scheme is only used in a few cases with high demands on the operating range [21]. The converter rating in the latter case is usually 20-30% of the machine rating, reducing the costs and power losses. Thus, the second scheme is the most popular one in current power systems [1].

Pump-turbine units with VS can regulate power in pumping mode, and therefore participate in the SRS as a controllable load. Other advantages are its wider operating range and higher hydraulic efficiency in generating and pumping modes.

In order to squeeze as much as possible the above-mentioned potential benefits of VS-PSHPs, it is necessary to implement certain features in the day-ahead scheduling. This entails to adapt and modify the Input/output curves of the pump-turbine units (I/O) as outlined in Fig. 1. The solid lines in generating mode (first quadrant) and the single dots in pumping mode (third quadrant) correspond to a pump-turbine unit with FS whereas the dotted lines in generating and pumping modes correspond to a pump-turbine unit with VS.

The real I/O curves in generating and pumping modes, with both FS and VS, will strongly depend on the pump-turbine performance curves and the electrical efficiency. As shown in Fig. 1, we have opted for the most common case, that corresponds to the following characteristics: the water discharge range in generating mode with VS is wider than the one with FS, both at the maximum efficiency head (Hmax) and at a lower head (H1); the power generation gc,t at design flow (qc,k) is lower with VS since the increase in hydraulic efficiency is lower than the decrease in the electrical efficiency; and the power consumption gp^v at design flow (q^v_k) is higher with VS since the increase in hydraulic efficiency is lower than the decrease in the electrical efficiency.
In order to participate in the secondary regulation reserve market, the maximum upward reserve, \( \max \ g_{d,s,up} \), in generating mode is the difference between the maximum minus the current generated power and the maximum downward reserve, \( \max \ g_{d,sw} \), in generating mode is the difference between the current minus the minimum generated power and the maximum downward reserve, \( \max \ g_{p,d,sw} \), is the difference between the current minus the maximum consumed power.

### III. Model Formulation

Model formulation is split in two Sections. Section III-A shows the model formulation of VS-PSHPs whereas Section III-B presents the model formulation of FS-PSHPs.

#### A. Model Formulation for VS-PSHPs

1) **Objective Function:** The objective function (1) maximises simultaneously the expected net income and the conditional value at risk, \( CVaR \). Each term is weighted according to \( \mu \), depending on the risk-aversion of the decision maker. Note that \( \mu = 0 \) corresponds to the risk-neutral decision.

The net income in scenario \( n \), i.e., \( B_n \), of a VS-PSHP participating in the DM and in the SRS in the framework of the Iberian electricity market [6] is defined in (2). Note that the model formulation is a scenario-based one without non-anticipativity constraints (NAC), as the energy and reserve schedule decisions are taken in a single-stage. The obtained solution is the same for all scenarios, and this fact might resemble the NAC. However, as there is no possibility to adapt the solution in a second stage, there are neither recourse functions so it does not seem appropriate to say that NAC is implicitly implemented. The decisions are robust to the uncertainty of the DM prices and the secondary regulation reserve market prices, thanks to the maximization of the CVaR. The reason why the authors have chosen to take both the energy and reserve schedule decisions in a single stage is motivated by the fact that the information disclosed after the clearing process of the DM has not a significant impact on the information used to take decisions in the secondary regulation reserve market in the Spanish electricity market (for instance, the correlation between the marginal prices of both markets was -0.47 in 2013). The first line in (2) expresses the net income for the secondary regulation energy due to the real-time use of the reserves. The second line accounts for the net income in the DM. The third line accounts for the income for the secondary regulation reserves put at disposal of the TSO in generating and pumping modes. And, finally, the fourth line represents the start-up costs in generating and pumping modes, respectively.

\[
B_n = \sum_t \left\{ \left( e_{t}^{s,up} \cdot \lambda_{up,t} - e_{t}^{d,sw} \cdot \lambda_{dw,t} \right) + \sum_c \left[ \left( g_{d,c,t} \cdot g_{c,t} \right) l_t \cdot \lambda_{D,n,t} \right] + \left( g_{d,c,up} + g_{c,t} + g_{p,c,up} + g_{p,d,sw} \right) \lambda_{S,n,t} - cSU_{c} \cdot y_{c,t} - cSU_{c} \cdot y_{c,t} \right\} \forall n
\]

Uncertainty is considered in the day-ahead energy prices and in the secondary regulation reserve prices because their values of perfect information (VPI) are significant. The VPI of the day-ahead energy prices can be up to 26% of the maximum theoretical income if the PSHP participates in the DM and in the SRS and up to 36% if it only participates in the DM, according to the results in [22]. Besides, the VPI of the secondary regulation reserve prices can be up to 10% of the maximum theoretical income according to unpublished results from the authors. Finally, and also according to unpublished results from the authors, the VPI of the secondary regulation energy prices and the real-time use of the reserves are much less important than the VPI of the DM prices and/or the secondary regulation reserve prices.

2) **Risk-Aversion Constraints:** Several techniques can be found in the technical literature to take into account the risk management in an optimization model. In [23], two techniques are compared: i) the introduction of a minimum profit constraint, by which a minimum profit is required for each scenario and ii) the introduction of a minimum \( CVaR \). Both techniques do not guarantee feasible solutions, which depend on the minimum profit and \( CVaR \) chosen. In the presented model formulation, the risk management is modelled in a similar way as in [24], which is based on [25], by equations (3) and (4). They represent simultaneously the \( VaR \) and \( CVaR \). Note that this approach corresponds to a linear formulation and that a feasible solution is always guaranteed.

\[
VaR - \frac{1}{\beta} \sum_n \pi_n B_n \geq CVaR
\]

\[
B_n \geq VaR - B_n \forall n
\]

3) **Water Balance:** The water balance, (5) does not include any water inflow because a closed-loop PSHP is considered in this article. Water limits are imposed to water volume variable, \( v_t \) in all time periods, (6). Water balance and limits in the lower reservoir are not included in the model formulation for simplicity.

\[
v_t = v_{t-1} + \sum_c l_t \left( q_{p,c,t} + q_{d,c,t} \right) \forall t
\]

\[
v \leq v_t \leq \pi \forall t
\]

In the upper reservoir, a target water volume is imposed, (7), where \( T \) stands for the last period of the time horizon. The target water volume is deemed as input data to the model and equals initial volume in the case study section.

\[
v_t = f \forall t, t = T
\]

The proposed model formulation is limited to closed-loop operation in order to focus the interest of the publication in
the operation of the plant with the existing water in the system and without considering extra water. However, it can be easily extended to open-loop operation by i) introducing the hourly natural water inflows of the upper reservoir in (5) and ii) including the water balance equation of the lower reservoir, considering the hourly water outflows.

4) Hydropower Generation: Two generation/consumption curves, \( k_1 \) and \( k_2 \) have been considered in the formulation, and correspond to two different reservoir levels. Each curve is selected using the binary variable \( d_t \) that only depends on the water volume of the upper reservoir (8) and (9), as we consider that the effect of the lower reservoir level on the net head is neglectable.

\[
v_t \geq \frac{1}{2} (1 - d_t) + \left( \frac{v + \frac{\pi - v}{2}}{n} \right) d_t \quad \forall t \quad (8)
\]

\[
v_t \leq \pi \cdot d_t + \left( \frac{v + \frac{\pi - v}{2}}{n} \right) (1 - d_t) \quad \forall t \quad (9)
\]

\[
g_c^d t \leq u_c^d t \cdot g_c^d k + q s_c^d t + \frac{\pi}{d} (1 - d_t) \quad \forall c, t, k = k_1 \quad (10)
\]

\[
g_c^d t \geq u_c^d t \cdot g_c^d k + q s_c^d t - \frac{\pi}{d} (1 - d_t) \quad \forall c, t, k = k_1 \quad (11)
\]

\[
g_c^d t \leq u_c^d t \cdot g_c^d k + q s_c^d t + \frac{\pi}{d} (1 - d_t) \quad \forall c, t, k = k_2 \quad (12)
\]

\[
g_c^d t \geq u_c^d t \cdot g_c^d k + q s_c^d t - \frac{\pi}{d} (1 - d_t) \quad \forall c, t, k = k_2 \quad (13)
\]

Generation/consumption curves of each pump-turbine unit with VS are modelled by equations (10)-(29), according to Fig. 1 in Section II; the formulation is based on the one proposed in [26]. The power generation is calculated from (10)-(13), as a function of \( d_t \) and \( u_{c,t}^d \). With equations (14) and (15), the maximum and minimum water discharges, which depend on the water level in the upper reservoir, are considered. In addition to this, the water discharge takes into account not only the flow that is used to produce the energy committed or scheduled in the DM but also the extra flow that is required in order to provide the upward regulation energy and the flow that is kept upstream in order to provide the downward regulation energy (16)-(19). The water discharge used for deploying the secondary regulation energy also depends on the water level in the upper reservoir.

Head dependency in consumed power and pumped water is modelled analogously by (20)-(29). The pumped water also takes into account the extra flow that is pumped in order to provide the downward regulation energy and the flow that is kept downstream in order to provide the upward regulation energy (26)-(29).

5) Secondary Regulation Service: The SRS in the Spanish electricity market comprises the hourly power reserve of each participant, that is committed in a day-ahead reserve market, and the reserve deployment requested by the TSO in the real-time operation.

The secondary regulation reserve bids are modelled through (30)-(38). Note that the auxiliary variables \( aux \cdot g_c^d k \) and \( aux \cdot q_c^p t \) avoid non-linearities in the formulation of the downward and upward secondary regulation reserve in generating and pumping modes, respectively, due to the head dependency in the available spinning reserve. When a unit is off in generating mode \((u_{c,t}^d = 0)\), there is no available secondary regulation reserve by (32), and \( aux \cdot g_c^d k \) will take a value greater than or equal to the expression in square brackets in (31) and lower than \( \frac{\pi}{d} \cdot k_2 \) by (33). In addition, when a unit is in generating mode \((u_{c,t}^d = 1)\), \( aux \cdot g_c^d k \) equals zero through (33). The same behaviour can be seen with \( aux \cdot q_c^p t \) in pumping mode with (35)-(37). Finally, the Spanish TSO requires the market agents to fulfil an hourly ratio between the upward regulation reserve and the total reserve in order to ensure certain equilibrium between the upward and downward reserves, preventing them from offering only upward reserves or only downward reserves (38).

\[
g_c^d t - aux \cdot g_c^d k \leq \frac{\pi}{d} (1 - d_t) \quad \forall c, t \quad (30)
\]

\[
g_c^d t - aux \cdot g_c^d k \leq \frac{\pi}{d} (1 - d_t) \quad \forall c, t \quad (31)
\]

\[
g_c^d t - aux \cdot g_c^d k \leq \frac{\pi}{d} (1 - d_t) \quad \forall c, t \quad (32)
\]
The secondary regulation energy in each period $t$ is remunerated according to the net energy, i.e., the upward regulation energy minus the downward regulation energy in generating and pumping modes (40) and (41). Analogously, if $\phi_t=0$, the PSHP must pay the downward regulation energy price. If $\phi_t=1$, $e_t^{d,up}=0$ by equation (41) and $e_t^{s,up}$ equals the right-side of equation (39). The secondary upward and downward regulation energy prices, (42). Moreover, a PSHP usually comprises a single penstock between the upper reservoir and the power station so it cannot operate simultaneously in generating and pumping modes, regardless of the number of pump-turbine units. Consequently, if there is at least one unit operating in pumping mode, no unit can be operated in generating mode, and vice versa (43).

Finally, start-up decisions are modelled in generating mode (44) and in pumping mode by (45).

$$\begin{align*}
g_{c,t}^{d,up} - u_{c,t}^{d,up} & \leq g_{c,t}^{p,up} - u_{c,t}^{p,up} \leq g_{c,t}^{p,up} \quad \forall c, t \quad (27) \\
g_{c,t}^{d,up} & \geq u_{c,t}^{d,up} - u_{c,t}^{d,up} - 1 \quad \forall c, t \quad (28) \\
g_{c,t}^{p,up} & \geq u_{c,t}^{p,up} - u_{c,t}^{p,up} - 1 \quad \forall c, t \quad (29)
\end{align*}$$

**B. Model Formulation for FS-PSHPs**

A FS-PSHP only regulates power in generating mode, losing the opportunity to participate in the SRS while the plant is pumping. The model formulation comprises equations (2)-(45) and the following modifications: 1) the maximum and minimum technical pumped water of each pump-turbine unit with VS, $q_{c,k}^p$ and $q_{c,k}^p$, have to be equal to the parameter $q_{c,k}^p$, i.e., the pumped water at synchronous speed and 2) the maximum and minimum technical power consumption of each pump-turbine unit with VS, $p_{c,k}^p$ and $p_{c,k}^p$, have to be equal to the parameter $p_{c,k}^p$, i.e., the power consumption at synchronous speed. Due to these modifications, $q_{c,k}^p$ is zero in all hours by (25), and the available secondary regulation reserves in pumping mode are zero by (34) and (35) since $q_{c,k}^p=p_{c,k}^p$ in all hours when the pump-turbine unit is in pumping mode.

**IV. CASE STUDY**

1) Electric Power System Data: The data of the Iberian and the Spanish electric power systems considered in this paper are the historical hourly values of: 1) the day-ahead energy prices, 2) the secondary regulation reserve prices, 3) the secondary upward and downward regulation energy prices, 4) the percentage of the real-time use of the upward and downward regulation reserves and 5) the ratio between the upward regulation reserve and the total reserve, $R_{SM}^s$, set by the TSO in advance of the secondary regulation reserve auction.

The uncertainty is modelled by one hundred scenarios ($n=100$ scenarios). Each scenario is composed by a 24-hour price profile of the DM prices and a 24-hour price profile of the secondary regulation reserve market prices. The scenarios are built by combining ten representative profiles of the DM prices with ten representative profiles of the secondary regulation reserve market prices. In order to generate such representative profiles of both the energy and reserve market prices, the following steps are carried out [27]: 1) the GARCH-ARIMAX model described in [22] is used for the DM prices, 2) a SARIMAX model is fitted for the secondary regulation reserve market prices. The scenarios are used by the TSO in advance of the secondary regulation reserve auction.

The real upward and downward regulation energy provided by each power plant in Spain is not publicly available. Thus, it is assumed that the hourly real-time use of reserves, $(\rho_t^{up}, \rho_t^{down})$ is given by the historical hourly ratio of the aggregate power delivery and the aggregate assigned reserves in the entire system. The hourly regulation reserve ratio, $R_{SM}^s$ is assumed to be the historical hourly ratio of the aggregate upward regulation reserve and the total reserve of the entire system.

2) Technical Data: Two different PSHPs are considered in this paper, each comprising two identical pump-turbine units. The PSHPs differ from each other in the pump-turbine Hill diagram considered in generating mode: i) the Hill diagram is taken from [28] (p. 509) and ii) the Hill diagram is the one of the Mt. Elbert PSHP units, taken from [29]. The performance of the pump-turbine units in pumping mode is determined from [30] with FS and VS, for both PSHPs. According to this, the following eight cases are studied:

- **FS-Raabe and FS-Elbert:** the units are equipped by a reversible Francis pump-turbine unit without frequency converter. Thus, they are operated at synchronous speed in generating and pumping mode.
- **VS-Raabe and VS-Elbert:** the units are equipped by a reversible Francis pump-turbine unit, a synchronous

2The MAPE of the proposed GARCH-ARIMAX model is 17.8% throughout 2014 whereas the one of the SARIMAX model is 21.2% in the same period.
machine and a full-scale frequency converter. Hence, they are operated with variable speed in generating and pumping mode. The electrical efficiency is assumed to be 98% [31].

- B-Raabe and B-Elbert: the frequency converters of the VS-Raabe and VS-Elbert are bypassed in generating mode, being operated the units with fixed speed in generating mode and with variable speed in pumping mode. Bypassing the converter in generating mode is achieved connecting the stator directly to the grid by means of the bypass switch. This operation can be found in the industry, for instance, in the PSHP of Grimsel II [19].
- VS-Raabe and VS-Elbert: the same situation of VS-Raabe and VS-Elbert but with doubly fed asynchronous machines. Due to this, the electrical losses in the frequency converters are lower. The electrical efficiency is assumed to be 99.7%.

Technical data of the pump-turbine units in the eight cases are presented in Table I. All data is split into pairs (except start-up costs): values on the left and the right of the slash refer to the I/O curve for the lower and the higher reservoir level, respectively. Part of the data was obtained from Guillaena PSHP in Spain: the higher gross head is considered to be 244 m, the lower gross head is assumed to be 219 m and the maximum water discharge has been chosen in order to empty the upper reservoir in a minimum time of 5.95 hours (the upper reservoir capacity is 2.21 $Mm^3$, $\bar{v} = 2.21 Mm^3/s$ and $\bar{v} = 0 Mm^3/s$). Hydraulic losses, mainly resulting from friction of the water in the penstock, are considered 3% of the gross head [32]. Finally, start-up costs in generating and pumping modes have been calculated according to [33].

### B. Methodology

The proposed models presented in Section III have been applied for all the above-described cases, to calculate the expected and Real Income (RI) in a representative 1-week period. The risk-averse weight factor and the confidence interval are fixed to $\mu = 0.1$ and 95% ($\beta = 0.05$), respectively. All the price scenarios have the same probability $\pi_n$. The economic results are compared to the maximum theoretical income (MTI), i.e., assuming perfect information in all the electric power system data. For these purposes, the models were run, day by day, over the one-week period and with a daily initial and final volume in the upper reservoir of 1.105 $Mm^3$ (7 problems for each case).

Based on the methodology used in [22], the RI is calculated in a post-optimization process by valuing i) the hourly energy schedule for the DM and ii) the hourly secondary regulation reserve schedule, both obtained from the optimization model, with the real historical hourly price of the DM and the secondary regulation reserve price, respectively.

From the results of all cases, we have 1) determined the extra value that the variable speed operation introduces comparing to FS-PSHPs when the plant only participates in the DM, and in the DM and the SRS and 2) analysed and compared the power and reserve schedule of FS-PSHPs and VS-PSHPs. Each daily problem is solved with a branch and cut algorithm in Cplex in a 2.4 GHz Intel Core i5-450M CPU, with 4 GB of RAM memory. In average, 100 minutes of CPU time were necessary to solve a whole week for each studied case. From the point of view of each daily model, the range of the CPU time was between 3-17 min.

### C. Economic Results

The RI and the MTI the for all cases are shown in Table II when the PSHP participates in the DM and in Table III when the PSHP participates in the DM and in the SRS. Revenues are composed of the day-ahead energy market income (DMI), which is split into sold energy when the plant is generating ($DM^+$) and purchased energy when is pumping ($DM^-$), the secondary regulation reserve market income (SM) and the income from the upward secondary regulation energy (ER2UP). Costs comprise the downward secondary regulation energy (ER2DW) and the start-up costs in generating mode, $cSU^{d}$ and in pumping mode, $cSU^{p}$.
Regarding the economic results participating only in the DM (see Table II), the introduction of the variable speed technology increases the RI and the MTI in all cases: between 3.7-8.2% and 2.5-3.8%, respectively, in cases with synchronous machines and between 10.1-12.2% and 6-7.2%, respectively, with asynchronous machines. The increase of the RI and the MTI with asynchronous machines is higher than with synchronous machines because of the increase in the electrical efficiency. If the converter is bypassed in generating mode, the RI and the MTI increase more than without bypassing the converters.

Regarding the economic results participating in the DM and the SRS (see Table III), the introduction of the variable speed technology increases the RI and the MTI in all cases much more: between 97-159% and 91-145%, respectively, with synchronous machines and between 102-163% and 95-150%, respectively, with asynchronous machines. This is due to 1) the participation of the PSHP in the SRS, 2) the increase in the operating range in generating mode with the variable speed technology and 3) the capability to regulate in pumping mode thanks to the variable speed technology. If the frequency converter is bypassed in generating mode, the RI and the MTI increase less than without bypassing the converters.

The results obtained when the frequency converter is bypassed in generating mode seem to be contradictory: the RI and the MTI increase if the PSHP only participates in the DM, and decrease if the PSHP participates in the DM and in the SRS. However, it can be explained as follows: when the frequency converter is bypassed, the higher electrical efficiency in generating mode yields a benefit in the DM, but the narrower operating range has a stronger negative impact in the reserve market.

In all cases, a big part of the revenue is obtained from the secondary regulation reserve market. This reflects that the PSHP is using the secondary regulation reserve as the priority source of revenue, and the DM as a subsidiary means to maximize the participation in the secondary regulation market.

### Table II

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### Table III

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regulation reserve market, the net profit from the upward and downward regulation energy increases. It is important to note that in the Spanish electric power system, the upward and downward secondary regulation energy prices are usually higher and lower, respectively, than the day-ahead energy prices (in 2014, the mean day-ahead energy price was 42.15 €/MWh whereas the mean upward and downward secondary regulation energy prices were 47.36 and 31.34 €/MWh, respectively).

Although analysing the sensitivity of the expected income (EI) and the RI to a variation in the risk-averse weight factor $\mu$ is outside the scope of the presented paper, Fig. 2 shows some interesting tendencies. Only the results for the VS-Raabe-A case are presented for the sake of clarity, being analogous for the rest of the cases. The EI and the RI are shown in the left y-axis whereas the VaR and CVaR are shown in the right y-axis of Fig. 2. As expected, the EI decreases but the VaR and CVaR increases, as the risk-averse weight factor increases. However, the decrease of the EI (between 0.1-0.27%) is lower in relative terms than the increase of the VaR and CVaR (between 0.38-0.99%). There does not seem to be any clear tendency of the RI with respect to the risk-averse weight factor. Finally, for all $\mu$, the RI is higher than the EI but the difference is less than 4% of the EI. This could suggest that the scenarios used to model the uncertainty is appropriate.

The inclusion of the VS technology does not only bring an extra income but also requires an extra investment cost. Although analysing the return of the investment of this technology is beyond the scope of the presented work, the following discussion can shed light about its profitability.

Investment cost related to PSHPs is strongly site-dependent. In the literature, several studies can be found regarding investment cost of FS-PSHPs. For example, [4] proposes a range between 470-2170 €/kW from the analysis of projects of FS-PSHPs in countries such as Spain, Portugal and Switzerland, among others, or [5], which proposes a range between 775-1280 €/kW from projects in Germany and Luxembourg. In addition, [34] proposes an increase between 7-15% of the investment cost of a FS-PSHP if the VS technology is included. According to the results obtained in Table II and Table III considering imperfect information, the FS-PSHPs obtain an income between 240-376 k€ and 92-114 k€ if they participate or not in the SRS, respectively, and the VS-PSHPs between 586-761 k€ and 100-125 k€ if they participate or not in the SRS, respectively. The investment costs of the FS-PSHPs are between 96-462 M€ using the installed capacity of Table I and the ranges proposed in the literature whereas the ones of the VS-PSHPs are between 105-517 M€, assuming an increase of 11% with respect to the former. Assuming that each PSHP obtains the same economic results in all the weeks, the pay-back periods of the FS-PSHPs are between 5.1-35.9 years and 17-93.1 years if they participate or not in the SRS, respectively. The pay-back periods of the VS-PSHPs are between 2.8-16.3 years and 17.2-94 years if they participate or not in the SRS, respectively. The inclusion of the VS technology would significantly decrease the pay-back period if the plant participates in the SRS and would slightly increase it if it only participates in the DM. Nevertheless, further research must be carried out to analyse the income of the plants for longer periods of time and taking into account the impact on the energy and reserve prices in case of a substantial increment of the number of PSHPs installed in the system able to provide SRSs while pumping.

D. Operation with Variable Speed Technology

The energy and reserve schedules of the FS-Elbert and VS-Elbert-A cases, and the amount of the upward and downward regulation energy delivered in real-time, according to the hypotheses described above, are shown in Fig. 3, for 11/11/2014. Note that the schedules shown in Fig. 3 were obtained considering uncertainty in the DM prices and in the secondary regulation reserve prices. The figure is divided into 5 subfigures where the following variables are depicted (note that all the variables presented in white bars correspond to the FS-Elbert case and those in black bars correspond to the VS-Elbert-A case): 1) the upper reservoir water volume of the FS-Elbert case in dotted line and of the VS-Elbert-A case in solid line, and the total water through the turbines (positive) or pumps (negative) in bars, 2) the energy schedule in bars and the historical price of the DM in solid line, 3) the reserve schedule in bars and the historical price of the reserve market in solid line, 4) the regulation energy in bars and the price of the upward and downward secondary regulation energy in solid and dotted line, respectively, and, finally, 5) the percentage of the upward and downward real-time use of reserves in solid and dotted line, respectively.

From the point of view of the decisions in the DM, in both cases, the PSHP generates and consumes energy in almost the same hours (except in hours 2 and 14-15). As can be seen in subfigure 1 and 2 of Fig. 3, in both cases, the PSHP pumps/discharges water to/from the upper reservoir during off-peak/peak hours (lower/higher day-ahead energy prices). However, in the VS-Elbert-A case, the PSHP generates and consumes less energy than in the FS-Elbert case, in most hours. This is due mainly to the fact that in the VS-Elbert-A...
Fig. 3. Optimal operation of FS-Elbert (white bars for flows, power and regulation energy and dotted line for volume) and VS-Elbert-A (black bars for flows, power and regulation energy and solid line for volume) in the day 11/11/2014. Upward and downward secondary regulation energy prices and the real-time use of reserves in solid and dotted line, respectively.

In the VS-Elbert-A case, the PSHP can participate in the reserve market in both generating and pumping modes (see hours 2-7, 12, 15-17 and 24 in subfigure 2 and 3 of Fig. 3). In the VS-Elbert-A case, the PSHP also benefits from the reserve prices during off-peak hours in the DM, which according to unpublished studies carried out by the authors, do have a negative correlation with the day-ahead energy prices, and are, therefore, usually higher during off-peak hours of the DM in the Iberian electricity system. In the VS-Elbert-A case, the operation of the PSHP is focused on making profit from the secondary regulation reserve market as it offers reserve every single hour (see subfigure 3 of Fig. 3).

E. Sensitivity Analysis

Three sensitivity analyses have been carried out in order to study the sensitivity of the income to a variation in 1) the secondary regulation reserve price, 2) the upward secondary regulation energy price and 3) the downward secondary regulation energy price. In each sensitivity analysis, the risk-neutral decision is taken (i.e., $\mu = 0$) and the electric power system data are chosen according to the following methodology.

1) The hourly historical data of the price under study in each day of the period 2010 to 10/11/2014 is clustered into four daily groups based on the method of the squared Euclidean distances [35].

2) The distance between each historical price profile and each centroid is measured by means of the Euclidean distance. Then the real daily historical price profile that is the closest to each centroid is chosen. Fig. 4 shows the centroids and the closest price profiles of the historical data used in the sensitivity analysis corresponding to the secondary regulation reserve price.

3) The other two price profiles are chosen directly according to the historical data in the days of the profiles chosen in the previous step. For instance, the prices profiles for the highest centroid in Fig. 4 correspond to 28/12/2013, being the real prices of the secondary reserve and the upward and downward secondary regulation energy of this day the ones that are used.

4) The day-ahead energy price profile is a single 24-sequence from the forecasting model proposed in Section IV-B in the day 11/11/2014.

5) The percentages of real-time use of the upward and downward regulation reserves and the ratios between the upward regulation reserve and the total reserve, $R_t^{SM}$, are those of the day 11/11/2014.

The results of the sensitivity analyses with respect to the secondary regulation reserve price, the upward secondary regulation energy price and the downward secondary regulation energy price are shown in Fig. 5-7, respectively. In each figure, the total income of all the PSHPs under the above-described assumptions is presented in the left y-axis. In addition, the average value of the price under study in the sensitivity analysis is shown in the x-axis (the four values in the x-axis correspond to the historical average value in the days corresponding to the profiles chosen in step 2). In the
sensitivity analyses of the upward and downward secondary regulation energy prices, the average value of the secondary regulation reserve price is also shown in the right y-axis in order to better understand the behaviour of the income.

The sensitivity of the income to the mean secondary regulation reserve price is significant, Fig. 5, varying the former fourfold when the latter varies sixfold. In the day under study, the sensitivity seems to be quite linear, being higher for VS-PSHPs than for FS-PSHPs. This sensitivity analysis confirms the results obtained in Section IV-C as regards the importance of the secondary regulation reserve market in the PSHP income. Thus, a change in the mean reserve price affects considerably the total income.

The sensitivity of the income to the mean upward secondary regulation energy price is also significant, Fig. 6, and also higher for VS-PSHPs than for FS-PSHPs. However, the total income curves are again explained by the mean secondary regulation reserve price (SM price), first decreasing and then increasing as the mean upward secondary regulation energy price increases. This result also confirms the ones obtained in Section IV-C regarding the small magnitude of the income from the upward secondary regulation energy comparing to the total income.

Finally, the sensitivity analysis of the mean downward secondary regulation energy price is similar to the one with the mean upward secondary regulation energy price, Fig. 7.

V. CONCLUSIONS

An MILP model for the energy and secondary regulation reserve scheduling of a PSHP with variable speed is presented. The model takes into account uncertainty in the day-ahead energy prices and in the secondary regulation reserve prices, and also the risk-aversion of the decision maker. Additionally, this study preliminarily quantifies the increase in the RI and the MTI, due to the operation with variable speed, of a PSHP participating only in the DM, and participating in the DM and in the SRS of the Iberian electricity system. The PSHP under study is assumed to be closed-loop, daily-cycle and price-taker.

The results obtained in the article show that a VS-PSHP could enlarge its income up to 12.2% when it only participates in the DM and up to 163% if it also participates in the SRS, comparing to a FS-PSHP. In addition to this, the results seem to indicate that VS-PSHPs equipped with doubly fed asynchronous machines might obtain a higher income than VS-PSHPs equipped with synchronous machines, and that when the frequency converter is bypassed in generating mode, higher income might be expected when the PSHP only participates in the DM, and lower income might be expected when the PSHP participates in the DM and the
SRS. It is important to consider these results in the context of a price-taker PSHP and a bidding procedure which considers uncertainty in the day-ahead energy prices and in the secondary regulation reserve prices. Further research, taking into account the uncertainty in the hourly secondary regulation energy prices and the real-time use of reserves, is required to obtain more realistic figures on the expected revenue of VS-PSHPs. Furthermore, considering a price-maker approach in the secondary regulation market, where the quota of each participant may be of considerable size, is deemed as another future work. Other trading options of the PSHP in, for example, intraday markets and the tertiary regulation service are worthy to be considered in future works.

REFERENCES

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