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

Introduction

Within the SP6 of the EERA Joint Program on Energy Storage, it is expected to analyze the techno-economic viability of energy storage technologies. As an example, it is here briefly presented the results published in [1].

The economic viability of twelve pumped storage hydropower plants (PSHPs) equipped with different fixed-speed and variable-speed units and with and without considering hydraulic short-circuit operation is studied. The analyzed plants are assumed to participate in the day-ahead energy market and in the secondary regulation service (also called the automatic frequency control service) of the Iberian power system. An optimization 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 (activation of the committed reserves).

Methodology

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 and the investment costs of the PSHPs. The maximum theoretical income is obtained from the results of the above-mentioned deterministic day-ahead energy and secondary regulation reserve hourly scheduling model, based on mixed integer quadratic programming (MIQP). It assumes 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. All analyzed PSHPs are considered to be of closed-loop and daily-cycle type. Most part of the technical data of the analyzed PSHPs have been provided by General Electric Renewable Energy from some of its last prototypes or studies.

In order to obtain the MTPB, the following three steps are carried out. In step 1, the maximum theoretical incomes are obtained, using the optimization models described in [2] for PSHPs with variable speed units and in [3] for PSHPs operating in hydraulic short-circuit mode and for PSHPs with fixed speed units. The investment costs are estimated in step 2, according to the available technical literature, and presented and discussed in [1]. Finally, in step 3, the economic viability is analyzed by means of the mentioned MTPB.

Pumped-storage hydropower plants

The twelve considered PSHPs are described as follows (please, the reader is referred to [1] for further information about the technical data of each unit):

1) FS-B (fixed-speed binary units): the units are equipped with a Francis pump-turbine without frequency converter.
2) FS-TF (fixed-speed ternary units with Francis turbines): the units are equipped with a Francis turbine and a pump, both without frequency converter.
3) FS-TP (fixed-speed ternary units with Pelton turbines): the units are equipped with a Pelton turbine and a pump, both without frequency converter.

4) VS-FF (variable-speed fully-fed): the units are equipped with a Francis pump-turbine and a synchronous machine connected to the grid through a frequency converter with the same power rating as the synchronous machine.
5) VS-BFF (variable-speed fully-fed with bypass): the frequency converter of the VS-FF is bypassed in generating mode by connecting the stator, via unit transformer, directly to the grid through a suitable bypass switch. This operation can be found in, for instance, the PSHP of Grimsel II [4], and the related data were not provided by General Electric Renewable Energy.
6) VS-DF (variable-speed doubly-fed): similar arrangement as VS-FF but with an induction machine whose rotor is connected to the grid through a frequency converter with a power rating lower than the one of the induction machine (normally below 30%, depending on the speed regulation range). Due to this, the absolute electrical losses in the frequency converters are lower.
7) SC-B (hydraulic short-circuit with binary units): similar arrangement as FS-B but with the possibility of operating in hydraulic short-circuit mode (one unit in pumping mode and the other in generating mode).
8) SC-TF (hydraulic short-circuit with ternary units with Francis turbines): similar arrangement as FS-TF but with the possibility of operating in hydraulic short-circuit mode.
9) SC-TP (hydraulic short-circuit with ternary units with Pelton turbines): similar arrangement as FS-TP but with the possibility of operating in hydraulic short-circuit mode.
10) SC-FF (hydraulic short-circuit with variable-speed fully-fed): similar arrangement as VS-FF but with the possibility of operating in hydraulic short-circuit mode.
11) SC-BFF (hydraulic short-circuit with variable-speed fully-fed with bypass): similar arrangement as VS-BFF but with the possibility of operating in hydraulic short-circuit mode.
12) SC-DF (hydraulic short-circuit with variable-speed doubly-fed): similar arrangement as VS-DF but with the possibility of operating in hydraulic short-circuit mode.

Results

As it is above-mentioned, the economic viability is analyzed using the MTPB. The calculation of the MTPB assumes that the interest rate and the expected increase of the maximum theoretical income due to an increase in the demand or the energy or reserve prices will be 0% in the whole pay-back period. Table 1 shows the estimated MTPBs. They are coloured with the following assumptions: green cells consider a MTPB lower or equal 25 years and that the investment in the PSHP is interesting, yellow cells consider a MTPB greater than 25 years and lower or equal 35 years and that the investment in the PSHP is partially interesting, and red cells consider a MTPB greater than 35 years and that the investment in the PSHP is not interesting. The colours are chosen arbitrarily taking into account the lifetime of the PSHP between 60 and 100 years [5].

Cost FS-B	FS-B	FS-TF	FS-TP	VS-FF	VS-BFF	VS-DF	SC-B	SC-TF	SC-TP	SC-FF	SC-BFF	SC-DF
0.5	12.8	10.8	7.5	5.6	7.4	8.6	12.9	8.9	5.9	5.6	7.4	8.6
1	25.5	21.6	15.1	11.2	14.7	17.1	25.8	17.9	11.8	11.2	14.8	17.2
1.5	38.3	32.4	22.4	16.7	22.1	25.7	38.7	26.8	17.7	16.8	22.2	25.8
2	51.1	43.2	29.9	22.3	29.5	34.2	51.6	35.7	23.6	22.4	29.5	34.4
2.5	63.9	54.1	37.4	27.9	36.9	42.8	64.5	44.7	29.5	27.9	36.9	42.9
3	76.6	64.8	44.9	33.5	44.2	51.3	77.4	53.6	35.5	33.5	44.3	51.5
3.5	89.4	75.6	52.4	39.1	51.6	59.9	90.3	62.5	41.4	39.1	51.7	60.1
4	102.2	86.4	59.9	44.6	59.1	68.4	103.2	71.5	47.3	44.7	59.1	68.7

Table 1. Minimum theoretical pay-back period, in years, with the considered investment costs (0.5–4 M€/MW of the FS-B PSHP). Green < 25 years, yellow between 25 and 35 years andred > 35 years.

The lowest MTPBs correspond to the VS-FF, SC-FF and SC-TP PSHPs, respectively, in all the investment cost cases. Assuming the above-mentioned lifetime of the PSHPs between 60 and 100 years, even the fixed-speed PSHPs with ternary units and without the possibility of operating in hydraulic short-circuit mode (FS-TF and FS-TP PSHPs), can be economically viable as long as their investment costs are lower than 2.64 M€/MW. This proves that the operation of the PSHPs also in the secondary regulation service (capacity and activation of the capacity) improves significantly the economic viability of PSHPs in comparison to the results if the PSHPs only participates in the day-ahead energy market (see for example [6]).

The use of fully-fed variable speed binary units (VS-FF PSHP) helps to decrease the MTPBs in all the FS PSHPs and in all the investment cost cases: by 56.3% with respect to the FS-B PSHP, by 48.3% with respect to the FS-TF PSHP and by 25.4% with respect to the FS-TP PSHP. Note that the increase or decrease of the MTPB between two PSHPs are the same in each investment cost case because the maximum theoretical incomes do not change. However, the MTPB of the PSHP equipped with fully-fed variable speed binary units increases by 32.2% if the converter is bypassed in generating mode (VS-BFF PSHP). The reason to this is that bypassing the frequency converter yields a higher electrical efficiency in generating mode in the VS-BFF PSHP but a narrower operating range in comparison to the VS-FF PSHP; the narrower operating range has a stronger negative impact for the participation in the SRS than the positive impact of the higher electrical efficiency in generating mode.

The use of doubly-fed variable speed binary units (VS-DF PSHP) decreases the MTPBs with respect to the FS-B PSHP (by 33.1%) and with respect to the FS-TF PSHP (by 20.8%), but to a lower extent than the VS-FF PSHP, and increases the MTPB with respect to the VS-BFF PSHP (by 16%). The reason to this is that the VS-DF PSHP has a narrower operating range in generating mode with respect to the VS-FF PSHP and in pumping mode with respect to the VS-FF and the VS-BFF PSHPs.

The possibility of operating in hydraulic short-circuit mode decreases in general the MTPBs of all PSHPs without the variable speed technology. However, the decrease strongly depends on the configuration of the PSHP. If the PSHP is equipped with ternary units and Francis turbines (FS-TF and SC-TF PSHPs), the MTPB is reduced by 17.2%. If the PSHP is equipped with ternary units and Pelton turbines (FS-TP and SC-TP PSHPs), the MTPB is reduced by 21%. Finally, if the PSHP is equipped with fixed speed or variable speed binary units (FS-B, VS-FF, VS-BFF, VS-DF, SC-B, SC-FF, SC-BFF and SC-DF PSHPs), the possibility of operating in hydraulic short-circuit mode does not appreciably modify the MTPB. The flexibility introduced by the hydraulic short-circuit operation is higher for the PSHPs with ternary units since both the turbine and the pump can operate simultaneously. The hydraulic short-circuit operation with binary units is performed by using one unit in pumping mode and the other in generating mode, and does not therefore add an appreciable flexibility to be offered in the SRS.

Conclusions

In order to conclude, 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.

References

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