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Optimal operation and hydro storage sizing of a wind–hydro power plant

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Abstract

Ambitious targets for renewable power production have been defined for the electric power systems in Europe. The accomplishment of these targets requires the increase in renewable energy production, namely from wind power generation. However, the intermittent nature of wind creates several problems to the power system operation and new approaches based on the combined use of wind power and energy storage technologies need to be developed. In this paper, the concept of the combined use of wind power production and hydro storage/production is exploited, through the development of an operational optimisation approach applied to a wind generator park with little water storage ability. The optimisation model defines the operational strategy to be followed for the hours ahead by a pump station and an hydraulic generator embedded in a wind/hydro pumping facility, using the Portuguese energy remuneration rules. The proposed methodology leads to considerable yearly profits for the wind generator production.

Keywords: Wind–hydro generation; Optimisation problem; Energy storage; Wind power

1. Introduction

Wind power generation (WG) has largely increased in the last years, namely in European countries, and it is expected that this trend will continue. This results from a general European Union (EU) policy for the promotion of renewable energy sources (RES) in order to contribute for the reduction of the greenhouse gas emissions. The EU Directive for the use of renewable energies points to a target, for 2010, of assuring that 22% of the total electricity production in EU will came from RES [1]. In order to obtain such an ambitious target, WG has to play here a key role.

WG suffers, however, from an intermittent characteristic due to the own diurnal and seasonal patterns of the wind behaviour. This requires that a large-scale integration of wind power in electric power systems needs to be carefully developed, together with the implementation of new operational concepts and management tools. This should be done through the implementation of new interruptability and controllability concepts of wind parks (in clusters or individually), considering also the capabilities of the different types of wind energy conversion systems and its complementarity's with energy storage. Any efficient development of such operation management tools requires also some kind of wind power prediction, in order to identify the best global operation strategy of the system and the wind parks profit. Using storage energy strategies will help wind generators to follow closely a given production plan, to improve their participation in the market, or just for the optimisation of their operation.

In the recent years the combined use of wind and storage capabilities has started receiving attention from the scientific community. Kaldellis et al. [2,3] proposed the use of two water reservoirs; a micro-hydroelectric power plant and a water pump station (WPS), to store the power generated from the wind park in low demand periods. In this work, the authors investigated the long-term economic viability of the WG improvement, for

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Greek islands isolated networks. Halldórsson and Stenzel [4] formulated a method for the wind variation compensation in deregulated power markets, using trading arrangements. Korpas et al. [5] presented a method for the scheduling and operation of WG using energy storage. In this paper, the authors used a dynamic programming algorithm for the operation strategy, and they proposed a general model for the energy storage management within Nordpool.

In Ref. [6], it is proposed an optimisation approach for the integrated daily operation of a wind park working with a small hydro unit. In the present paper, the research described in Ref. [6] is extended, including an extensive description of the economic profits obtained from the operational cooperation of the wind and hydro units and the identification of the optimal size of the coupled water reservoir. Special attention is given to the formulation of the optimisation problem (wind park developer profit maximization), taking into account-specific physical and technical restrictions.

The remuneration characteristics of Portuguese law, regarding the Special Regime Production (which is the case for WG), are considered here. Since only wind (OW) energy is used for pumping purposes, all the energy delivered to the network (wind and hydro using the stored water) is remunerated as wind energy.

In the present paper, only active power management is modelled. However, targets related with reactive power production can also easily be considered. A Linear Primal Dual Interior Point algorithm solves the optimisation problem.

2. The small size water plant

The present paper proposes the improvement of the WG controllability through the addition of a small size water storage plant. For this purpose, the following devices are required:

(a) A mini hydroelectric power plant (mHPP) with an electric generator;
(b) A WPS;
(c) Lower and upper water reservoirs;
(d) Penstock and pumping pipes.

Equipments (a) and (b) can be replaced by a reversible hydro unit. The WPS (b) pumps water from a source (i.e. river, lake, other reservoir) to the upper water reservoir, only using the electrical power generated by the WG. However, the hydro components and the wind plant can be situated in different places, in the present work it is supposed an electrical proximity between them. An extension of this model, not analysed in the present paper, regards the utilisation of a pump station to control a cluster of wind parks.

3. The optimisation problem

The optimisation problem was formulated here in order to maximize the wind park profit in the operation of the wind–hydro system. In this formulation it is also possible to include an additional operational restriction related with the interest in following a curve of minimum active power demand for the next hours, such that it can be marketed as a kind of a firm power transaction. When this is found not to be possible, it estimates the additional capacity of the water reservoir (or the initial level of the reservoir) required to follow the demand curve, if it exists.

The inputs of the optimisation problem are here: curve of predicted wind power; curve of minimum demand to be supplied; curve of maximum allowable power exchange with the system; curve of active energy price for selling to the grid; and pumping operational cost.

Numerous techniques have been developed to provide forecasts for the available wind power for short and medium term time horizons [5,7–9]. In fact, wind and wind power forecast techniques have already reached a considerable maturity. Such approaches are important for the identification of the optimum strategies to be followed in the system operation. Using the wind forecasts, the wind power curve characteristic and the wind generators availability, the curve of forecasted available electric wind power can be obtained. Wind power forecasting can also be directly performed for 48 h ahead, as described in Ref. [9], with enough accuracy. In the present work it is assumed the availability of a series of predicted values of wind power for a 2 days period in advance.

In some cases, the energy stored in the upper water reservoir allows to supply the required demand even if the available wind power is lower. Therefore, a curve of minimum demand to be supplied can be defined. Presently, in Portugal the distribution utility and the transmission system operator are obliged to accept all power produced by the WG plants, such that they are considered as non-dispatchable power plants.

Due to some network operational conditions resulting mainly from limits in the system branches, not all the power generated by wind parks can penetrate in the system. Then, a curve of maximum allowable power exchange with the system should also be defined, modelling limitations in the penetration of wind power in the network.

In Portugal, the WG active power price is defined by governmental laws [10,11]. In other countries, the curve of active power price is defined by the spot market and should be forecasted, taking into account the expected market behaviour.

For the solution of this problem, daily operation was discretized in 24 hourly periods. For each time interval, the developed approach provides the following results: the total active power foreseen to be delivered to the grid; the power that is expected to be produced by both wind and hydro generators; the power consumptions of the pump unit; and the level of the upper water reservoir.

The definition of the daily operation of the wind–hydro (W–H) plant is obtained from the solution of the following optimisation problem:

$$\max. \sum_i (c_i P_i - c_{\mathrm{p}} P_{\mathrm{p}_i}) - c_{E^{\mathrm{M}}} \Delta E^{\mathrm{M}} - c_{E_1} \Delta E_1 \tag{1}$$

$$\text{s.t.} \quad P_i = P_{\mathrm{w}_i} + P_{\mathrm{h}_i} \tag{2}$$

$$P_{\mathrm{v}_i} = P_{\mathrm{w}_i} + P_{\mathrm{p}_i} + P_{\mathrm{DL}_i} \tag{3}$$

$$E_{i+1} = E_i + t\left(\eta_{\mathrm{p}} P_{\mathrm{p}_i} - \frac{P_{\mathrm{h}_i}}{\eta_{\mathrm{h}}}\right) \tag{4}$$

$$E_1 = E_1^{\mathrm{esp}} + \Delta E_1 \tag{5}$$

$$E_{n+1} = E_{n+1}^{\mathrm{esp}} \tag{6}$$

$$P_{\mathrm{L}_i} \le P_i \le P_{\mathrm{ex}_i} \tag{7}$$

$$P_{\mathrm{h}^{\mathrm{m}}} \le P_{\mathrm{h}_i} \le \min\left(P_{\mathrm{h}^{\mathrm{M}}}, \eta_{\mathrm{h}} \frac{E_i}{t}\right) \tag{8}$$

$$P_{\mathrm{p}^{\mathrm{m}}} \le P_{\mathrm{p}_i} \le P_{\mathrm{p}^{\mathrm{M}}} \tag{9}$$

$$0 \le E_i \le (E^{\mathrm{M}} + \Delta E^{\mathrm{M}}) \tag{10}$$

$$(P_{\mathrm{DL}}, \Delta E, \Delta E_1) > 0, \quad i = 1, \ldots, n \tag{11}$$

where the variables are:

P_i	active power delivered to the network by the wind–hydro plant, during the *i*-interval;
P_{w_i}	active power delivered to the network by the wind generator, during the *i*-interval;
P_{h_i}	active power produced by the hydro generator, during *i*-interval;
P_{p_i}	active power consumed by the WPS, during *i*-interval;
P_{DL_i}	dump power load, i.e. active power of the wind power curve not used to generate electricity, during *i*-interval (equivalent to wind power to be curtailed or reduced, if technologically possible);
E_i	energy storage level in the reservoir, during *i*-interval;
ΔE^{M}	additional capacity of the upper reservoir, relatively to E^{M};
ΔE_1	additional initial energy in the reservoir, relatively to E_1;and the corresponding parameters are:

and the corresponding parameters are:

P_{L_i}	minimum power demand to be supplied, *i*-interval;
P_{v_i}	available wind power, *i*-interval;
P_{ex_i}	maximum allowable power exchange with the system, *i*-interval;
c_i	active power price, *i*-interval;
c_{p}	pump cost (€/MW h);
E^{M}	reservoir storage capacity;
$c_{E^{\mathrm{M}}}$	penalty for storage upper E^{M};
c_{E_1}	penalty for initial storage upper E_1^{esp};
η_p	efficiency of WPS and water pipes network;
η_h	efficiency of the water reservoir and hydro generator;
E_1^{esp} and E_{n+1}^{esp}	initial and final levels of the reservoir, respectively;
$P_{\mathrm{h}^{\mathrm{m}}}$ and $P_{\mathrm{h}^{\mathrm{M}}}$	lower and upper power limits of the hydro generator, respectively;
$P_{\mathrm{p}^{\mathrm{m}}}$ and $P_{\mathrm{p}^{\mathrm{M}}}$	lower and upper power limits of the pump station, respectively;
t	duration of each discrete interval;
n	number of discrete intervals (24).

The objective function (1) is constituted by three components. The first seeks to maximize the profit in the active power delivered by the wind–hydro plant to the grid. The second component of (1) has two goals: for an existent reservoir, it calculates the minimum amount (if necessary) of incremental storage capacity to follow the specified demand curve; in the planning stage, it obtains the lower storage capacity in the reservoir to follow a pre-determinate demand curve, for a specified forecasted wind power curve. The third component of the objective function (if $c_{E_1} > c_{E^{\mathrm{M}}}$) seeks the convergence of the optimisation problem when the requested demand is superior to the available power. For existing reservoirs, $\Delta E^{\mathrm{M}} > 0$ or $\Delta E_1 > 0$ implies in a problem without real solution.

From Eq. (2), the total amount of active power supplied to the network is composed of the hydro generation plus the portion of wind generation directly sent to the system, in each interval.

The available wind power, in each interval, is used to supply active power at the network and to pump water to the upper reservoir, according to Eq. (3). In some special cases, a portion of this available power cannot be utilized ($P_{\mathrm{DL}_i} > 0$).

At the beginning of the $(i+1)$-interval, the available energy in the reservoir is the initial value in the *i*-interval plus the energy pumped by the WPS, minus the amount of energy supplied to the grid by the mHPP in that period (Eq. (4)).

Eqs. (5) and (6) specify the initial and final values of energy in the reservoir for the study horizon.

The W–H plant should supply, at least, the values specified as demand curve in each period of the day, according to Eq. (7).

Eqs. (8) and (9) allow to respect the mHPP and WPS limits, in all periods. From Eq. (8), the upper limit for the hydro unit generation is the minimum between its physical limit and the available energy in the reservoir.

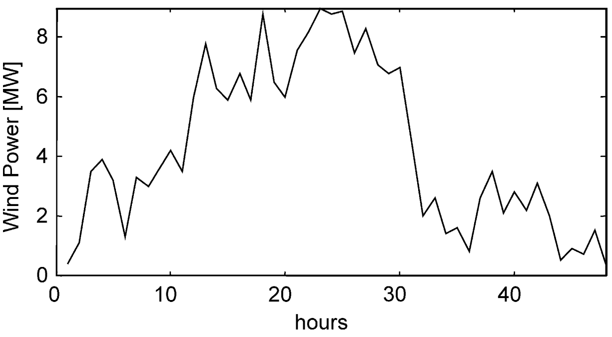

Fig. 1. Forecasted available wind power.

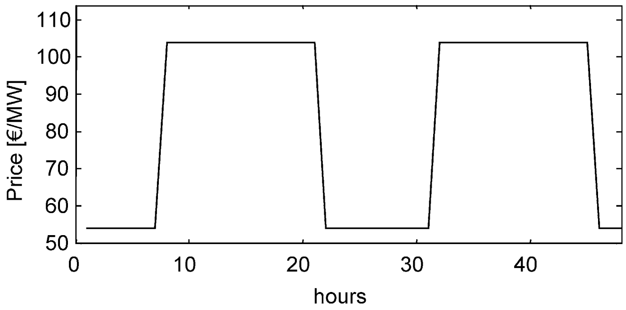

Fig. 2. Active power price.

In usual conditions, the reservoir can store energy up to a maximum value (Eq. (10)). If it is not possible to reach the demand targets, the maximum value of the reservoir is increased ($\Delta E^M > 0$).

The solution of the optimisation problem, defined by Eqs. (1)–(11), was obtained in MatLab environment using a primal–dual interior point method.

4. Results

4.1. Daily operation

In Figs. 1 and 2, the input curves describing the forecasted available wind power and active power price are shown, for a 2-days horizon period ($n = 48$).

Fig. 1 is a typical wind power curve of an 11 MW wind park installed in mainland Portugal. The curve of Fig. 2 describes the remuneration defined in the Portuguese laws for the wind power plants, if the daily modulation coefficient is exploited [10,11].

In Table 1, other characteristics of the W–H plant are shown.

In Table 1, the global efficiency of the hydro network is described by $\eta_L = \eta_h \eta_p$, being the installed capacity of the wind park given by P_g^M.

To decrease the investment costs, the installed capacity of the pump station and the hydro generator are less than 20% of the installed capacity of the wind park (2 MW). The storage capacity was defined to be 22 MW h, which corresponds to a 2 h operation at nominal WG power. In the first simulations, the reservoir at the initial and final periods is considered empty. The pump cost was considered to be a low value, representing in this way only the operational internal cost. It is important to stress that the efficiency and the active power consumption of the pump station were specifically considered in the formulation.

In the first case, the maximum allowable power exchange with the system is considered as fixed during all periods ($P_{ex_i} = 6$ MW $\quad \forall i$). No minimum production profile was defined ($P_{L_i} = 0 \quad \forall i$). This operation seeks to obtain the maximum economic profit in operational conditions, assuming that no transactions agreement had been settled.

In Fig. 3, the active power outputs of the W–H operation vs. OW operation of the plant are depicted. In low price periods (white boxes) the OW output (dotted line) is generally greater than the W–H operation (solid line). In these periods and in W–H operation, water is pumped to the upper reservoir, to increase the active power to be delivered to the grid during the upper price periods (grey boxes).

It can be observed, from Fig. 3, the influence of the limit of the maximum allowable power exchange with the system (hours 13–30). In the OW operation, the existence of dump loads is simulated in order to assure that the output power is kept below the level accepted by the network, namely when the maximum power exchange with the system is reached. This assumption is, however, optimistic since usually the conventional OW policy consists in the disconnection of wind generators, to avoid over passing the maximum power exchange limit with the grid. The differences between the results of this connection–disconnection strategy and used OW strategy (dotted line shown in Fig. 3) will result in larger gains for the W–H operation, since the disconnection of wind generators will provoke, in general, a loss of production larger than the load dumping effect. This evaluation is not considered in the present paper. On the other hand, it should be stressed that in W–H operation the wind turbine production are not curtailed during this period, since an important portion of the remaining wind energy surplus is now stored in the upper reservoir through the pump station.

Table 1
Wind–hydro plant characteristics

P_g^M (MW)	P_h^M (MW)	P_p^M (MW)	η_L	c_p (€/MW h)	E^M (MW h)	E_1^{esp} (MW h)	E_{n+1}^{esp} (MW h)	c_{E^M} (€/MW h)	c_{E_1} (€/MW h)
11	2	2	0.75	2	22	0	0	199	299

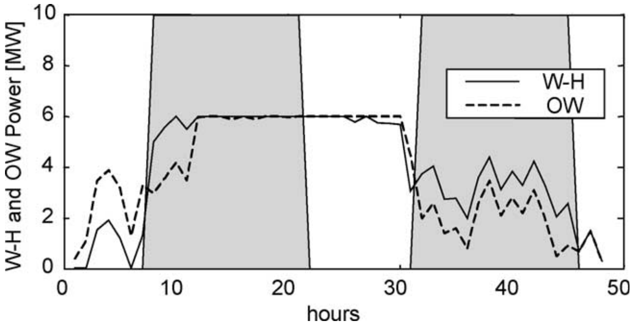

Fig. 3. Wind–hydro and only wind generation.

Fig. 4 shows the participation of the wind and hydro generators production in the W–H plant power output.

As shown in Fig. 4, the hydro generator (dotted line) only operates in high price periods. The mHPP obtains a greater utilization efficiency (68%) in the second high price stage, after a low price–high wind period. In Fig. 5, the WPS operation is shown.

From Fig. 5, one can see that the WPS is principally used in low cost periods. Its utilization efficiency in both of these periods is high (88 and 92%, respectively). In the first high price stage, the limit of maximum allowable power exchange with the system is reached (Fig. 3) and there is unused wind power capacity (Fig. 1). In this case, water is pumped instead of the reduction in the wind power production.

In Fig. 6, the total wind power production and the non-used available wind power are shown.

The production of the wind turbines is the sum of its direct contribution for the active power delivered to the grid plus the WPS consumption, in each period (Eq. (3)). From Figs. 4 and 6, it can be observed that the wind turbines produce above the limit of maximum allowable power exchange with the system, decreasing, in this way, the available wind power that would not be used. The W–H plant cannot use 3.79 MW h (1.85%) of available wind power. Instead, the OW operation policy does not use 24.94 MW h (12.2%) of the available wind power resource.

From Fig. 6, it can be seen that the available wind power is not used in the W–H plant when its consumption limits (6 + 2 = 8 MW) are reached (i.e. maximum allowable power exchange with the system (power delivered to the grid) plus upper limit of the pump station).

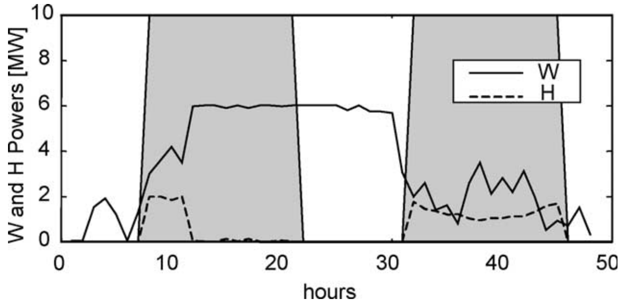

Fig. 4. Wind and hydro active power outputs.

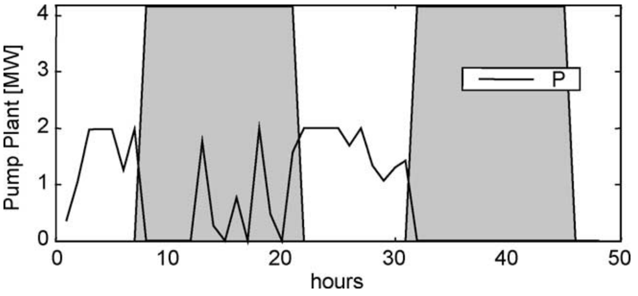

Fig. 5. Pump station consumption.

In Fig. 7, the storage levels in the upper reservoir for all periods in the study horizon are depicted.

During the low price periods, the upper reservoir always increases its storage level (Fig. 7). In the first high price period, the storage can be increased because of the remaining available wind power. The storage in the reservoir reaches its peak values when high price periods began. Just before the end of second low price period, the storage level reaches its maximum limit (22 MW h).

In Table 2, the profits between W–H and OW operations are compared.

The profits described in Table 2 were obtained for the active energy outputs of both operation policies (Fig. 3) using the price curve of Fig. 2 (in W–H strategy, minus the pump costs due to the WPS consumption, Fig. 5). In the considered period, the operation of the wind plant with hydro storage capacity increases the profit in 13.22% (Table 2). Assuming that the specified conditions are the same during all the year, the annual gain in the operation would be in the amount of 356,560 €.

In Table 3, the numbers of equivalent hours of operation at nominal power of the wind generators, for OW and W–H operation strategies, are presented. Assuming the repetition of the 48 h wind power profile as valid for all the year, the increase in the WG amount, that results from the use of the W–H operation strategy, allows an increase of 7.6% in the number of annual equivalent hours at nominal power for the plant.

In Fig. 8, the profits obtained between W–H and OW operation are compared, when the installed capacity of the wind park changes from 0 to 15 MW.

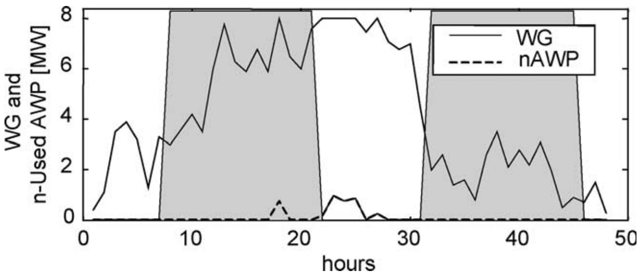

Fig. 6. Total wind generation and non-used available wind power.

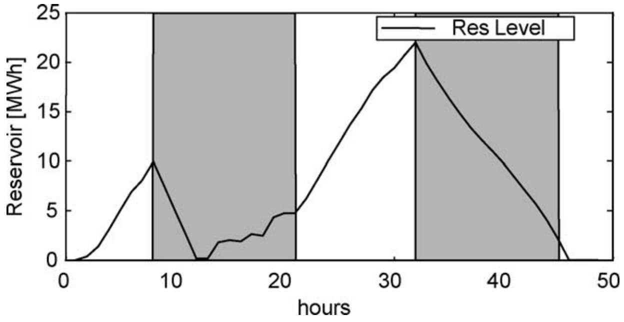

Fig. 7. Storage levels in the upper reservoir.

From Fig. 8, four different behaviors can be observed regarding operational profits between W–H and OW operation, when the wind generator upper limit (P_{g^M}) is changed. This picture displays two alternatives to increase the profit in a W–H operation. In a first phase ($0 < P_{g^M} < P_{p^M}$), the proposed strategy allows to increase the profit because of the differences in the active energy hourly price. This gain depends on the storage ability utilization and becomes constant when the maximum hydraulic participation capacity is reached. The second benefit is obtained when there are restrictions that affect the delivery of all the available wind power to the grid in some periods. In this case, the OW operation must reject a portion of the available energy. On the other hand, W–H strategy can store this energy to sell it latter, if economically interesting.

As previously explained in the definition of the optimization problem, the proposed representation of the W–H operation (Eqs. (1)–(11)) enables the calculation of the optimum maximum storage capacity in the upper reservoir, for pre-specified operation conditions and forecasted wind power availability. This estimation is accomplished assigning a low value to the penalty (c_{E^M}) for storage capacity upper the pre-specified E^M value. In the present case, $c_{E^M} = 0$ is used. The optimum value for the storage ability is obtained by the maximum value requested in all periods. For the present conditions, the optimum storage capacity in the reservoir is 31.91 MW h.

Table 2
Wind–hydro plant vs. only wind operation-profit

Only wind (€)	Wind–hydro (€)	Two-days gain		Annual gain (€)
		(€)	(%)	
14,767	16,721	1954	13.2	356,560

Table 3
Wind–hydro plant vs. only wind operation—equivalent hours at nominal power

Two-days				Annual		
Only wind (h)	Wind–hydro (h)	Gain		Only wind (h)	Wind—hydro (h)	Gain (h)
		(h)	(%)			
16.32	17.56	1.24	7.6	2978	3204	226

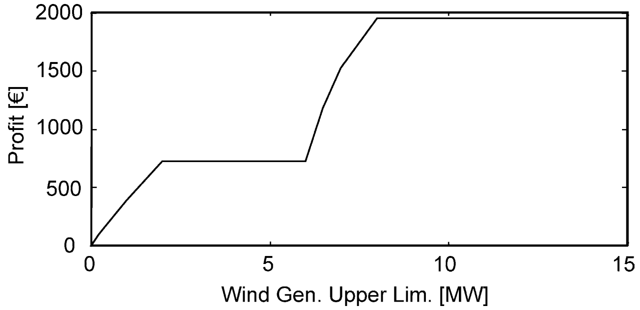

Fig. 8. Variation in the Wind Park installed capacity. W–H vs. OW profit.

4.2. Yearly operation

A 12-month simulation was performed assuming that the wind profile was changed by a seasonal modulation. Fig. 9 shows typical variations of the mean wind speed in a site of North-Portugal for the different months of the year. These values are presented in p.u. relatively to values of January 2002.

The optimization problem was extended to a full year, considering 365/2 wind power profiles of 48 h (Fig. 1), including a seasonal wind variation in each month by multiplying the wind power hourly values by the seasonal modulation p.u. values (Fig. 9).

The results of yearly simulation are shown in Tables 4(a) and (b).

In Tables 4(a) and (b), the line of *Average* values is obtained by calculating the arithmetic mean value of the elements of corresponding upper column. The percent profit was, however, obtained through a weighted arithmetic mean value. The profits shown in Table 4(a) regard the gains of W–H vs. OW operation.

As shown in Table 4(a), larger wind power production availability generally results in higher monthly percent profits. However there is a non-linear relation among these values due to the specific W–H operational strategy implemented during each month. In the present simulation, the larger seasonal modulation is in month 6 (1.28 (p.u.), 12.18%), but the larger percent profit corresponds to months 2 and 11 (1.03 (p.u.), 13.77%). The seasonal wind power

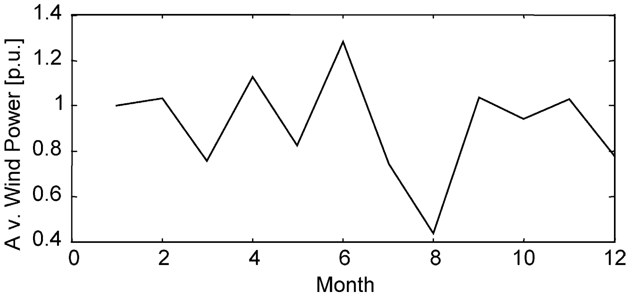

Fig. 9. Available wind power (p.u.)—seasonal modulation.

Table 4(a)
Yearly simulations—profit

Month	Profit			Seasonal Modulation (p.u.)
	Month		Annual (k€)	
	(€)	(%)		
1	1953.75	13.22	356.56	1.00
2	2065.25	13.77	376.91	1.03
3	869.23	7.31	163.75	0.76
4	2051.54	13.21	374.41	1.13
5	1170.70	8.93	213.65	0.83
6	1998.66	12.18	364.75	1.28
7	860.52	7.11	157.04	0.74
8	644.26	8.96	117.58	0.44
9	2064.81	13.75	376.83	1.04
10	1758.07	12.31	320.85	0.94
11	2062.06	13.77	376.33	1.03
12	966.93	7.70	176.46	0.78
Average	1541.15	11.92	281.26	0.92

Table 4(b)
Yearly simulation—mean power and storage

Month	Maximum storage capacity (MW h)	Mean power		Seasonal modulation (p.u.)
		W–H (MW)	OW (MW)	
1	22.00	4.00	3.74	1.00
2	22.00	4.11	3.79	1.03
3	21.67	3.06	3.15	0.76
4	22.00	4.24	3.92	1.13
5	21.67	3.35	3.36	0.83
6	22.00	4.46	4.13	1.28
7	21.33	3.01	3.12	0.74
8	21.29	1.72	1.86	0.44
9	22.00	4.11	3.80	1.04
10	21.95	3.80	3.63	0.94
11	22.00	4.10	3.79	1.03
12	21.57	3.15	3.22	0.78
Average	21.77	3.59	3.46	0.92

variation described in Fig. 9 implies a yearly reduction of 8% in the average available wind power. However, this decrease implies in a larger yearly profit reduction, from 356,560 € (month 1) to 281,260 € (21.11%) in the year.

In Table 4(b), the used maximum storage capacity and the average of the active powers delivered to the grid are described. For the lower available wind power production profiles, the storage ability is not fully employed.

The value of the yearly mean active power delivered to the grid (Table 4(b)), when adopting the W–H operation (3.56 MW), is slightly greater than in OW strategy (3.46 MW). However, as maximum operational profit is searched in this optimization approach, instead of maximizing the active power that can be delivered to the system, in some months the W–H operation supplies less active power to the grid than the OW policy. In months 3, 5, 7, 8 and 12, the W–H operation provides active power values inferior to the ones delivered through the OW operation, providing respectively percent gain increases of 7.31, 8.93, 7.11, 8.96 and 7.70.

5. Conclusions

An optimization approach was described here to help identifying the best strategy for the operation of a combined wind–hydro pumping storage power plant. From the solution of the optimization problem it is possible to determine the hourly operation of the WPS, mini hydro generator and wind generator, such that it will increase the power plant operation profit. Results of the application of this approach in near real operation conditions are presented. Furthermore, the proposed model can be used to assist in the hydraulic design of the W–H plant, calculating the optimal equipment specifications. Two strategies aiming to obtain gains in the W–H operation were considered: (a) through energy transferred between periods with different prices and (b) through storage of the available wind power production when it is greater than the transmission power acceptance limit imposed by the network.

A yearly simulation, considering wind data from a site in of North-Portugal, is presented in the paper. Interesting gains are obtained, when comparing the wind–hydro strategy (determined through the optimization approach described in the paper) versus the OW operation.

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