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Pump hydro storage and gas turbines technologies combined to handle wind variability: optimal hydro solution for an Italian case study

M. Bianchi[a], L. Branchini[b]*, A. De Pascale[a], A. Peretto[a],F. Melino[a], V. Orlandini[a]

[a]Alma Mater Studiorum – University of Bologna, DIN – Viale Risorgimento, 2, Bologna 40136, ITALY
[b]CIRI-EA-Alma Mater Studiorum – University of Bologna – via Angherà, 22, Rimini 47900, ITALY

Abstract

Load and wind energy profiles are totally uncorrelated, therein lies the problem of variable energy sources. Managing load with increasing wind penetration may call for operational ranges that conventional systems cannot readily access. Storage technologies could allow tolerating the unsteadiness of renewable sources with smaller fossil fuel plants capacity. Pumped Hydro Storage (PHS) is a crucial technology for balancing large steam power plants and may become increasingly important for storing renewable energies. Hence capacity ranges of PHS as well as its dynamic response to renewable power variability, will become progressively relevant. An integrated system made of a wind farm, a PHS plant and a set of gas turbines (GTs), as programmable fossil fuel devices, to handle renewable variability and maximize renewable energy exploitation, is studied in this paper. A specific case study is analyzed: a wind farm with a nameplate capacity equal to that installed in Sardinia is considered. To match the power output requested by the region with the integrated systems different configurations of PHS plant will be investigated. The impact of reversible or separate Francis machines with constant or variable speed will be analyzed in order to minimize electric power output overproduction and GTs fuel consumptions. Minimum and maximum capacity range for reversible or separate machines will be considered. The aim of the study is the optimum sizing and design of a PHS unit in a hybrid wind-hydro-gas turbine power plant to match the load request. Results in terms of PHS operation, water height behavior in upper and lower reservoirs, GT units power output, natural gas consumed and electric power output overproduction will be presented for each analyzed case.

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Keywords: Pumped hydro storage; Energy storage system; Integrated systems; Renewable source, Plant sizing, Gas turbine

1. Introduction

* Corresponding author.Tel.: +39-0512093320; fax: +39-0512093313.
*E-mail address:*lisa.branchini2@unibo.it

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Renewable sources power penetration has increased rapidly in the last decade: at the end of 2012, the global installed renewable power capacity reached 480 GW. In particular, global wind power installed capacity increased by 12.4% to more than 318 GW in 2013 [1]. Generally, the renewable energy sources are naturally intermittent. However, wind energy results more variable compared to other Renewable Energy Sources (RES), because wind velocity is a highly fluctuating meteorological parameter. This nature of the RES causes a challenge for grid stability. Therefore, the Energy Storage Systems (EES) are now a necessity in a power system to meet peak load, improve the stability, maintain the balance and the frequency control of the electric grid [2]. Between the all EES technology, the Pumped Hydro Storage (PHS) is generally viewed as the most promising technology to increase renewable energy penetration levels in power systems and particularly in island grids. Thus, PHS accounts for more than 99% of storage capacity worldwide, corresponding around 127 GW[3]. The objective of this paper is to compare the performances of a PHS system using different hydro machines operating ranges and set configurations integrated with renewable and conventional sources while matching the load request. The research contribution of the study is to define the optimal PHS runners set (type and capacity) in order to maximize renewable sources exploitation, i.e. to avoid or, at least, minimize wasting of renewable energy. More in details, the considered integrated system has been sized to reproduce the real case of the Sardinia Italian region, where, at the beginning of 2011, the net wind nameplate capacity installed was about 950 MW [4]; while, the reference PHS power plant main characteristics refer to Taloro power plant (Sardinia): installed runners are three reversible Francis and the plant rated power production is 240 MW in pumping mode and 219 MW in generating mode with a head higher than 290 m [5, 6].

Nomenclature

AERO	Aeroderivative
EES	Energy Storage Systems
GT	Gas Turbine
HD	Heavy Duty
LHV	Lower Heating Value
P	Pump
PHS	Pumped Hydro Storage
RES	Renewable Energy Source

2. Integrated hybrid system

2.1 Wind data and load profiles

In order to analyse the behaviour of the integrated system in different wind conditions, several days, representative of a high, medium and low wind power output, have been considered to generalize the studied methodology. More in detail. four days have been chosen, each one as characteristic of a year season. Therefore, the overall investigated time period is equal to 96 hours as reported in Fig. 1.aWind power output data have been derived from available normalized real 1 minute data. The operational data regard various wind farms located in a wide area[7]. The considered wind farm has a nameplate capacity equal to 940 MW, corresponding nearly to the net capacity installed in Sardinia at 2011 [4]. Moreover, the figure.shows the power output provided to the grid, supposed variable in time. The region requested load has been evaluated as a percentage of the Italian load. The percentage has been set equal to the 3.3%, calculated as the ratio between the total yearly amount of electric energy needed by the region grid and the one needed by the Italian grid [8]. The daily load profile refers to the load requestedwith 1 hour as time step. [9]. As a consequence, the minimum value (base load) of the grid load is equal to 911.7 MW (red line in Fig. 1.a). Assuming the base load guaranteed by thermoelectric plants installed on the island, the integrated system has to deliver a 527 MW maximum load. The required load has been supposedidentical for the four analysed days.Fig.1.b shows the difference between the load curve and the wind power production during the considered days. The figure. allows to identify the underproduction and overproduction periods, i.e. when, respectively, the PHS plant needs to generate energy and when it could store energy as water in the higher reservoir.

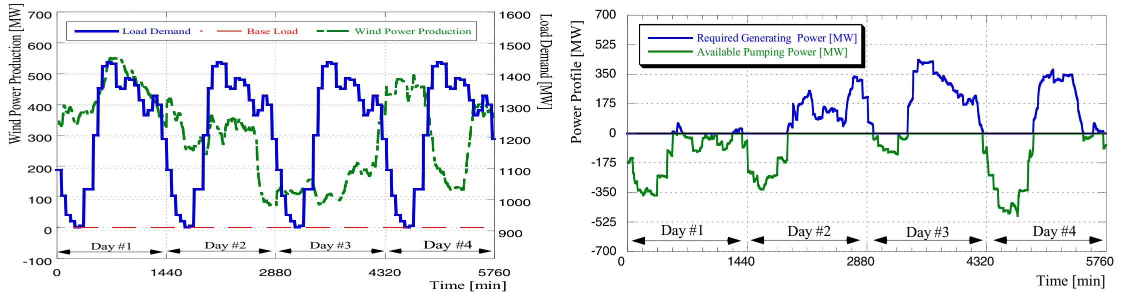

Fig. 1.(a) Wind farm power output and load demanded by the grid; (b) Difference between wind farm power production an load required

Gas turbinescharacteristics

In order to investigate the influence of gas turbines (GTs) performance and efficiency on the capability to fill wind power output fluctuation and variability, both the aeroderivative (AERO) LMS 100 and the heavy-duty (HD) SGT6-5000F gas turbines have been considered. Both GTs have been selected for their quick ramping regulation, high efficiency, even at partial load and fast starting.More in detail, the HD unit can be initialized to minimum loadin 5 minutes from hot start up and it can be loaded at 30 MW/minute. This permits 150 MW within 10 minutes; the reduction in starting time is over 60% with respect to common heavy duty GTs [10]. While, the AERO unit provides full load operation in less than 10 minutes from a cold start up and in 5 minutes from a hot one [11]. All of these characteristics are extremely important when GTs are used to smooth out renewable variability [12]. More information about GT design parameters could be found in Bianchi et al. [13].Besides, the total power provided by the GT units (308 MW), along with the maximum power of PHS plant (in generation 219 MW), is enough to make up the firm power output, even if no power from wind is available. The efficiency of AERO GT is higher compared to HD GT both at full or partial load, so regulation of aeroderivative GT should be preferred over heavy duty one even if, when compensating power is extremely high only HD machine can provide it.

2.2Pumped hydro storage characteristics

The main real specifications of PHS plant and of hydro machines are listed in Table 1 [5]. Pumped storage is assumed to be eitherin pumping or generating mode. The Francis runners are assumed as variable speed machines: the main advantages of this configuration are higher efficiencies in turbine mode and the capability to adjust the pump load to the network needs. It results in a wider range of regulating capacities: typically between 60% and 100% in pumping mode, while between 15% and 100% in generation mode [14]. Pumped storage here is represented by a water storage reservoir, with the inefficiencies associated with pumping and generating accounted for when filling the reservoir. Penstock losses are also accounted in PHS model (the penstock efficiency has been considered equal to 97.5%). The pump and turbine efficiencies, for sake of simplicity, are assumed to be constant even at partial load. A maximum variation of reservoir height (i.e., a limitation in the dispatchable volume of water between reservoirs) has been imposed in accordance to PHS real operation. Both pumping and generating are subject to ramping and minimum and maximum capacity constraints, as any other unit. However, a PHS unit usually has a very high ramping rate. A 8 minutes resolution, assumed as time step for simulations, guarantees that storage can go from full pumping capacity to full generating capacity within the assumed time interval. At the beginning of simulation, volume inside upper reservoir has been fixed equal to

$11.2 \cdot 10^6$ m^3, meaning that half of the total amount of dispatchable volume is available for PHS operation. The dispatchable volume of water can be transfer in generation mode from upper to lower reservoir in 45 hours.

Table 1. Main specifications of PHS plant [5].

Turbine	Generating Range Power [MW]	10.95 ÷ 73	Reservoirs	Max. water volume inside reservoir [10^6 m^3]	18.8
	Volumetric flow rate [m^3/s]	31.07		Min. volume inside reservoir [10^6 m^3]	3.60
	Turbine Efficiency [%]	85		Dispatchable volume [10^6 m^3]	15.2
Pump	Pumping Range Power [MW]	52 ÷ 80		Surface of reservoirs [km^2]	1.20
	Volumetric flow rate [m^3/s]	20.06		Max. water height inside reservoir [m]	296
	Pump Efficiency [%]	75		Allowed water height variation [m]	14.0

3. Regulation Strategy

A calculation code has been developed in VBA Script™ language. The regulation algorithm, able to calculate GTs and PHS operation, is widely described in Bianchi et al. [15]. The aim of the strategy is to maximize the energy captured from fluctuating wind by wind turbines and minimize natural gas fuel consumption trying to avoid or, at least, minimize overproduction during load demand satisfaction. The calculation code, at each time step, needs as input data load and wind power profiles. It provides, as output data, GTs and PSH power profiles during the day along with water height inside reservoirs, the amount of natural gas consumed for GTs operation including start-up and shutdown procedures, etc. In case of GTs operation, the algorithm takes into account the GTs limitations in minimum turn down ratio and different GTs LHV efficiency at part load. GTs control strategy was implemented by choosing as many units as possible in full load to meet the requested power output. The difference was provided by units that could meet partial load called by wind variations.

4. Parametric analysis for optimal PHS design

4.1 The input data

The parametric investigation analyses three pumping mode configurations of the PHS plant: in the first case the use of reversible hydro machines is considered, while the other cases analyse the possibility to use separated pumps and turbines, with the aim of identify the advantages related with the installation of different pumping capacities. More in details, case A coincides with the existing plant set configuration: the hydro machines are three identical reversible Francis runners, each one able to cover from 10.95 to 73 MW in generating mode and from 52 to 80 MW in pumping mode. Meanwhile, in case B and C, separated hydro turbines and pumps have been considered: in generating mode the power capacities are the same of case A (see Table 1), while pumps capacities (P1, P2 and P3)and allowed pumping power range are reported in Table 2.For each pump in case B and C, the ratio between minimum and maximum capacity has been set equal 65%, as in the real case.The method chosen to identify the best pumps capacities is described by Beevers et al [16]and it allowsto increase the accessible pumping range. The ratio between the hydro machines capacities are available for every size: the presented study is a particular case, totally generalizable. Thus, the three configurations have different pumping ranges,graphically reported in Fig. 2. More in detail, the total amount of pumping capacity is nearly the same in case A and B, but case A presents a pumping capacity hole between 80 ÷ 104 MW.Having a continue pumping capacity means that the PHS plant is able to exploit a higher range of renewable power overproduction. In case C, the overall installed capacity is higher than in cases A and B and the biggest pump (i.e. P3) has a maximum power corresponding to the total installed capacity in the other cases, as visible in Table 2

Table 2. Pumping mode capacity of the considered hydro machines for the analysed cases.

			case A (real plant)	*case B*	*case C*
Pumps	Power Range [MW]	**P1**	52 ÷ 80	31.9 ÷ 49	65.7 ÷ 101
		P2	52 ÷ 80	49 ÷ 75	101 ÷ 156
		P3	52 ÷ 80	75 ÷ 115	156 ÷ 240
	Maximum Pumping Power [MW]		240	239	497

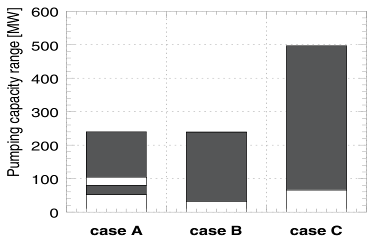

Fig. 2. Pumping capacity in the three Total cases

5. Results

Fig.3 shows the power produced by the hydro turbines and the installed GTsunder the considered wind power production and load request. The shown profiles are the same for the three considered cases, due to the high water volumes available in the reservoirs;the amount of natural gas consumed, due to GTs operation, in the four days is equal to about 516 t. Moreover, the GTs averaged operational efficienciesresult 34.4 % for the HD and 42.8 % for the AERO. Fig. 4 instead shows the pumps behaviors during the examined days: it can be observed how configuration of case C allows to exploit higher surplus of renewable energy than cases A and B; while the lowest pump capacity of the installed pump P1 in case B allows to exploit also the low values of power overproduction.

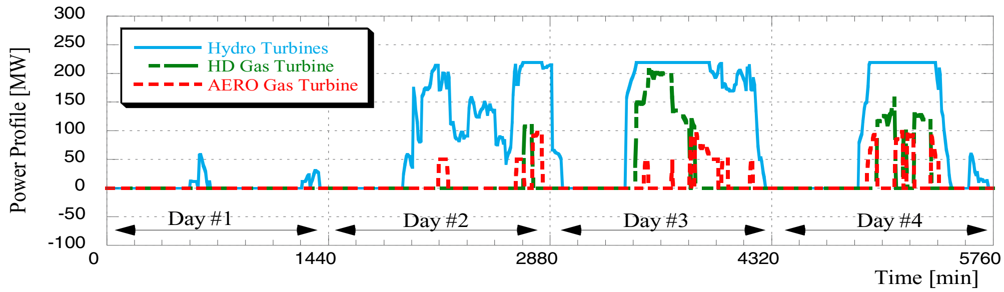

Fig. 3. Power production of the hydro and gas turbines obtained in each analysed case

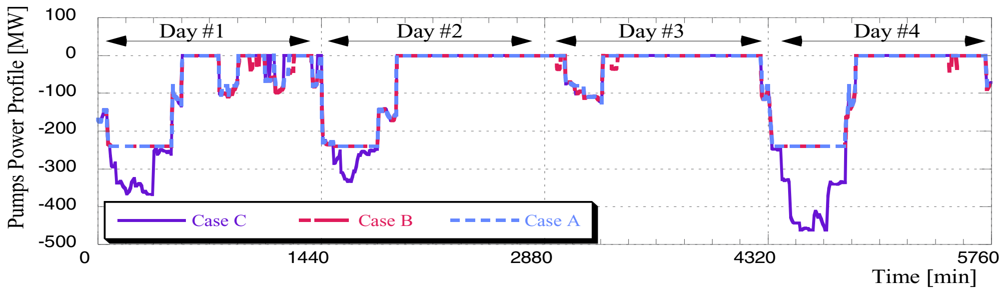

Fig. 4. The pumps power profiles in the three examined cases (Case A, Case B and Case C).

Finally, Table 3 lists the total amount of wasted renewable energy, i.e. the wind power not stored as potential energy into the upper reservoir: the installation of separated pump and turbines allows to reduce this value, as shown the small difference between case A and B. Moreover, the table shows the increasing of the final water volume in the upper reservoir, hence the stored available energy. The possibility to use highest pump, as in case C, increasesalso the pumping capacity of the PHS and exploits higher range of renewable power, reducing the wasted overproduction.

Table 3: Wasted renewable energy and stored water volume at the end of four days.

		case A	*case B*	*case C*
Wasted renewable energy	GWh/period	16.31	15.05	2.99
Final water volume	10^6 m^3	285.85	285.98	287.21

6. Conclusion

This study analyses the function of a hypothetical integrated system, consist of wind farm, gas turbines and a PHS plant,sized on real values based on Sardinia Italian region. Besides, the effects of the using of reversible pump-turbine or separated hydro machines have been estimated. Splitting pumps and turbines allow to have a continue range of pumping capacity, in addition to an increasing of the overall capacity. Thus, the integrated system can maximize the renewable sources exploitation, reduce the wasting of renewable energy and store a higher quantity of water in the upper reservoir, i.e. a higher quantity of energy, available for the following pick of required load.

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