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Simulation and size optimization of a pumped–storage power plant for the recovery of wind-farms rejected energy

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Abstract

The hybrid wind–hydro power generation appears to be an attractive solution for isolated, autonomous electric grids in order to increase the wind energy penetration and cost-effectiveness. This work presents a numerical methodology for optimum sizing of the various components of a reversible hydraulic system designed to recover the electric energy that is rejected from wind farms due to imposed grid limitations. The algorithm is applied to study a practical case using time variation data of rejected power from a number of wind farms installed in the island of Crete, Greece. The free design parameters of the system include the turbine size, the size and the number of the pumps, the penstock diameter and thickness, and the reservoirs' capacity, whereas some critical financial parameters are also considered. The numerical procedure combines an evaluation algorithm that simulates in detail the plant operation during a 12-month period, and an automated optimization software based on evolutionary algorithms. The economic analysis uses dynamic evaluation methods and the attainability of various objectives is examined using single or multi-objective optimizations. In addition, the developed numerical tool is used to perform several parametric studies and sensitivity tests in order to analyse in depth the influence of the most important parameters on the plant operation and economic behaviour. The results showed that a well optimized design may be crucial for the technical and economic viability of the examined system.

Keywords: Optimum sizing; Pumped–storage plant; Wind–hydro power generation; Autonomous electric grids; Energy storage; Wind energy penetration

1. Introduction

The wind farms installed on the islands are very frequently obliged to reject an amount of the produced energy due to penetration limits in the local electric grids that are usually small and not interconnected. For large islands, with important wind energy potential and wind farms of significant installed power, a considerable amount of energy that may exceed 10% of the produced is rejected during a year [1]. On the other hand, in small to medium sized islands the production cost of electricity using small thermal power plants can be very high, above 20 or even 25 €/MWh [2,3]. Although most of these islands exhibit significant wind potential, the stochastic nature of the latter along with the diurnal and seasonal variations in energy demands do not allow for adequate exploitation.

An attractive solution to recover the rejected wind energy and at the same time to increase the penetration of the wind farms in autonomous grids appears to be the construction of reversible hydraulic systems, in which the rejected energy will be transformed to hydraulic energy by a pumping station and stored to an elevated water reservoir [2–8]. The stored hydraulic energy can then be re-transformed to electricity by operating a hydraulic turbine. The possibility of constructing a pumped–storage unit in autonomous electric grids is of great importance in order to reduce the cost of thermal plants, since such a unit has a considerable value in its own right and can operate not only with wind farms but with any other power production systems [9,10].

Some detailed numerical algorithms for the simulation of hybrid renewable plants have been recently developed [2,7,9]. The use of wind–hydro hybrid schemes for some medium sized Greek islands is studied by Kaldellis et al. [2,5] using a detailed calculation procedure and examining

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the effect of some design parameters, as the wind-park size or the reservoir capacity. Also, a feasibility study for the island of Ikaria is presented in [3,8]. The results were very encouraging, showing that the wind–hydro combination is the best solution that overcomes problems of energy shortage or excessive electricity production. Moreover, an additional advantage of a pumped-storage unit is the possibility of using the water stored in the reservoirs for consumption or irrigation purposes, as also for protection against fires.

The first wind–hydro hybrid scheme in Greece is currently under construction by PPC in Ikaria Island [11]. It is expected to produce 23 GWh/yr, with about one-third of that coming from the pumped–stored hydraulic energy.

In the present work the surplus energy rejected by some typical wind farms installed in the island of Crete, Greece is used as pumping energy to raise water to an upper reservoir. The stored hydraulic energy is then used to produce guaranteed electric power in a water turbine for an agreed time-period every day. Given the time records of the rejected power, the optimum dimensioning of the pumped–storage plant that maximizes the recovered fraction of the rejected energy and the economic results of the system constitutes the aim of the present numerical investigation.

2. The examined case

The Greek island of Crete is a characteristic case of a high wind potential and increasing energy demands area, having an autonomous electric grid. Renewables have found significant acceptance by the people of Crete, and the installed wind generators in operation were 70 MW by the end of year 2002, while another 50 MW are under design or construction. The installed power of the base thermal units is about 600 MW. Their technical minima were of the order of 100 MW in 2002, and it is estimated to reach about 140 MW by 2011.

The three wind farms under consideration are installed in Siteia, Lasithi and contain 50 wind generators with a rated power of 25 MW, which corresponds to 36% of the total wind power installed in the island. Using the available data from the recording systems of the farms for some recent years [12], the time records of the mean wind velocity and then the total wind power production can be estimated by projection methods for the next years. Considering also the estimations for the absorbable wind energy into the local grid, and the corresponding increase of the totally installed wind power on the island, it is possible to make predictions for the time variation of the rejected power. Fig. 1 illustrates such estimations for the year 2006. As can be observed in Fig. 1a, rejections are minor during the summer, due to the increased power needs in this highly tourist period, but are significant during the rest of the year. Also, the profile is extremely non-uniform, exhibiting high peaks and variability, as also long periods with no rejection at all. Fig. 1b reveals that rejection is performed only in about 18% of the time, and only during 10% of the time the rejected power exceeds 5 MW. The sum of energy rejected during the year is estimated by integration to about 9800 MWh, approaching 13% of the produced energy. This is a considerable amount of energy and its recovery would provide remarkable economic and environmental benefits.

The main components of the energy recovery system considered here are shown in Fig. 2. The free design variables include the number and size (nominal flow rate) of the identical pumps operating in parallel mode, the size of the hydraulic turbine, the water pipe diameter and wall thickness, and the storage capacity of the reservoirs. The location of the two storage reservoirs is known from a site study; hence the static head, as well as the length of the water pipe are fixed to 280 m and 3250 m, respectively. Given are also the time variation of the rejected energy (Fig. 1) and the hydraulic turbine operation period that covers the peak demand hours 11:30–13:30 and 19:30–21:30, namely 4 h/day.

In order to always preserve an adequate for the subsequent turbine operation water content in the upper reservoir, supplementary energy from the main grid can be consumed to operate the pumps when the energy rejected from the wind farms is insufficient.

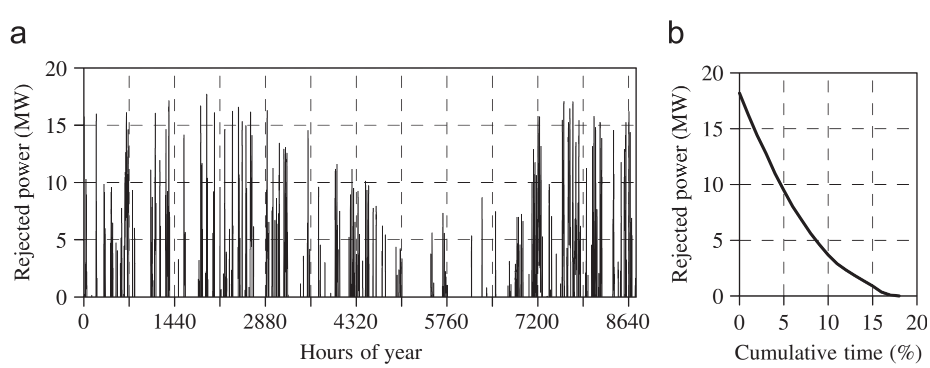

Fig. 1. Rejected power characteristics: (a) time record; (b) duration curve.