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Frequency control support of a wind-solar isolated system by a hydropower plant with long tail-race tunnel

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ABSTRACT

Pumped storage hydro plants (PSHP) can provide adequate energy storage and frequency regulation capacities in isolated power systems having significant renewable energy resources. Due to its high wind and solar potential, several plans have been developed for La Palma Island in the Canary archipelago, aimed at increasing the penetration of these energy sources. In this paper, the performance of the frequency control of La Palma power system is assessed, when the demand is supplied by the available wind and solar generation with the support of a PSHP which has been predesigned for this purpose. The frequency regulation is provided exclusively by the PSHP. Due to topographic and environmental constraints, this plant has a long tail-race tunnel without a surge tank. In this configuration, the effects of pressure waves cannot be neglected and, therefore, usual recommendations for PID governor tuning provide poor performance. A PI governor tuning criterion is proposed for the hydro plant and compared with other criteria according to several performance indices. Several scenarios considering solar and wind energy penetration have been simulated to check the plant response using the proposed criterion. This tuning of the PI governor maintains La Palma system frequency within grid code requirements.

1. Introduction

Generally, fossil fuels are very expensive in islands, principally because of transportation cost. Nevertheless, many islands have an excellent local wind and solar potential, so that economic, environmental and social costs of fuel electricity generation may be avoided. In last years, renewable energy sources have been used to substitute fossil fuels in small isolated systems [1–4].

One of the economic and technical drawbacks of the high participation of intermittent energy sources in isolated systems is the need to reject substantial amounts of the produced energy due to penetration limits in the local electric grids [5]. This affects to both, wind and PV generation.

The vast majority of studies agree that the introduction of storage systems is the most effective mean to significantly increase wind penetration levels in power system [5–8]. Pumped storage hydropower plans (PSHP) can contribute to this role, being able to compensate uncertainly in intermittent renewable energy (wind and solar). In fact, some current research is focused on the feasibility of the combination of solar, wind and hydro energy in islands (Fig. 1) [9]. This issue is also being considered in small isolated systems on some inland areas [10].

In some cases, sites available for building new PSHP may require long hydraulic conduits due to geographic, environmental or economic constraints. The main technical problem associated with long pipes is related to elastic phenomena, especially in those cases where for economic and environmental constraints no surge tank is built. In long pipelines, under-pressure and overpressure downstream or upstream of the turbine may result from the gate position movement. As an example, in long discharge pipes, cavitation phenomena may appear downstream the turbine due to an excessive suction pressure caused by gate closing movements [11].

The construction of a realistic model that takes into account all the phenomena involved in system operation is essential in order to draw relevant conclusions, applicable to predict the response of the station during design phase [12].

In particular, when the tail-race tunnel has a great length, the rigid-water-column models are not adequate [13] and consequently the controller settings based on it [14]. There are several researches which describe how to model the dynamic response

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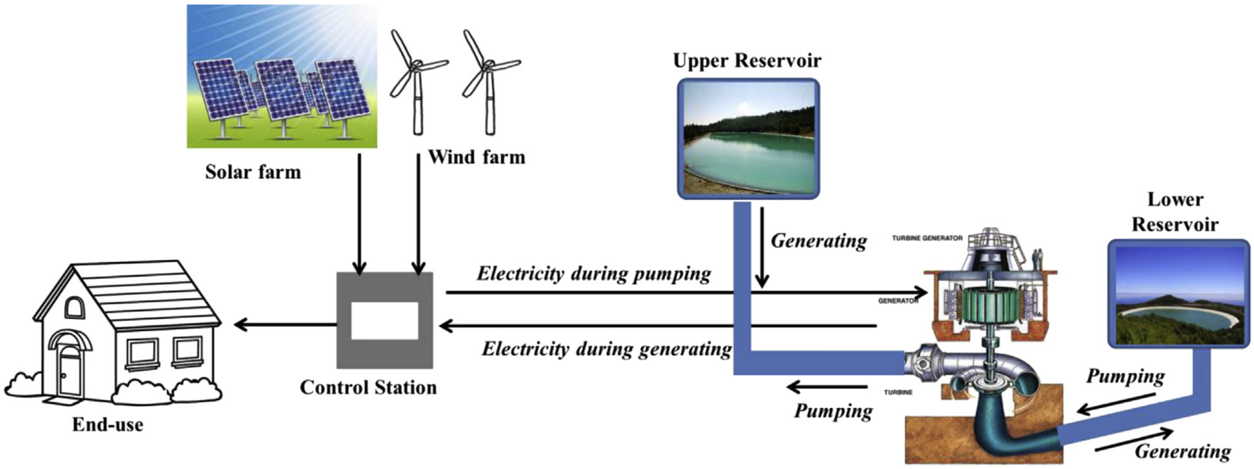

Fig. 1. A hybrid solar-wind system with pumped storage system.

when elastic phenomena cannot be neglected [15–19].

The use of PI controllers in hydropower plants to control speed governors is a usual practice [20] and several criteria for gain tuning have been developed in last decades [21–23]. Classic Control techniques, as root locus plot, have been successfully applied in order to obtain recommendations or expressions for PID speed governor tuning in the plant design phase [21,24–26], but this rules do not include water elasticity effects.

Regarding long pipes, very few studies have been found in the literature focused on the adjustment of PID governor gains in such cases. In Refs. [27], a hydropower plant with long penstock is modelled. In this study, authors propose two criteria to adjust PI gains assuming isolated system and wind energy penetration. In Refs. [28], a hydropower plant with long tail-race tunnel is modelled. In this case, the plant is aimed to contribute to secondary regulation.

La Palma is an island belonging to the Canary Islands archipelago and declared a Biosphere Reserve by UNESCO since 2002. Currently, the vast majority energy is provided by thermal plants, while only a small proportion is provided by wind and solar farms. The objective for next years is to reduce consumption of fossil fuel and increase the use of renewable resources [29]. For this purpose, it is expected to increase the installed capacity of wind and solar farms and to build a PSHP. One of the main objectives to be achieved is that at certain times, the energy is produced exclusively from renewable sources, thus overriding the thermal generation. In this case, the contribution of the hydropower plant to frequency regulation becomes very important, since the possible contribution of modern wind generators entails a cost: some wind energy will be lost [30].

In this paper, a PSHP in La Palma Island has been predesigned and modelled taking into account the penetration increasing rate of renewable energies (wind, solar and hydro) in recent years [31], as well as several published expansion plans [29–32].

In order to model the hydropower plant adequately, a detailed model which includes nonlinearities, head losses and distributed elasticity effects has been used. According to this aim, it is necessary to obtain the PI gains that allow to PSHP operate correctly. A methodology based on root locus plot to obtain these gains, taking into account water and tail-race tunnel elasticity effects has been developed. For this purpose, a simplified linearized model is obtained using the adjusted lumped parameter approach [16,17,27]. With this simplified model, an analysis in the frequency domain is developed, obtaining the transfer function of the control loop and the participation factor of each variable [18,23].

The adequacy of the proposed criterion for controller adjustment has been checked by comparison with other criteria, using some performance parameters belonging to the frequency and time domains (gain margin, phase margin, damping ratio…) as proposed in Ref. [33]. In order to evaluate the plant dynamic response due to different perturbations [34] (and its ability to operate in an isolated system with high penetration of solar and wind power) several simulations have been carried out. No contribution to frequency regulation from the wind farm has been considered.

The paper is organized as follows. In Section 2, the power system of La Palma Island (Canary archipelago) and the projected pumped storage hydropower plant are described. In Section 3, the hydropower plant dynamic model is presented, describing each element of the PSHP. In Section 4, a reduced order model is used in order to analyze the system in frequency domain. In Section 5, a tuning criterion based on root locus method is formulated, being compared with others classic ones. In Section 6, some real cases are proposed in order to simulate the PSHP dynamic response with the tuning criterion proposed. Finally, in Section 7 main conclusions of the paper are properly summarized.

2. Power system and PSHP description

The amount of electrical energy generated in 2013 on the island of La Palma was 262,375 MWh of which only 9.1% came from renewable sources, while the remaining 90.9% was produced by fossil fuels. The maximum peak demand for that year was 42 MW [31]. In order to reduce the share of fossil fuels, the authorities of the island of La Palma intend to carry out a major project to increase the penetration of renewable energy [35].

Currently, the installed generation capacity from fossil fuels is 82.8 MW in diesel generators and 22.5 MW in gas turbines. The renewable sources are shown in Fig. 2, including four wind farms (W) distributed throughout the island with an installed capacity of 9 MW and two solar photovoltaic (Pv) plants with an installed capacity of 4.9 MW [31]. In the last years, several expansion plans have been developed in order to increase the penetration of renewable energy throughout the archipelago [29,32]. According to the penetration rate of these energies in recent years [31] and taking into account the development plans of the energy system [32] it is considered that the most likely action would be to install a wind farm of about 20 MW. In this scenario, it would be necessary to have sufficient power regulation capacity in a pumped storage hydroelectric plant (PSHP) for integration of the other renewable energy sources [35,36].