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Dynamic analysis of island systems with wind-pumped-storage hybrid power stations

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ABSTRACT

Combined wind and pumped-storage virtual power plants, called hybrid power stations (HPS), constitute a realistic and feasible option to achieve high renewable energy source (RES) penetration levels in power systems and particularly in autonomous island grids. Technical issues arising from the integration of HPS in islands have not been sufficiently investigated yet. In this paper, the dynamic behaviour of an island system with an HPS is analysed, the effects of the various HPS operating modes on the transient behaviour and stability of the system are investigated, constraints regarding the operation of the HPS are identified and potential solutions are proposed.

1. Introduction

Energy storage is considered as the most effective means to significantly increase wind penetration levels in power systems [1,2], particularly in the case of isolated island grids where technical limitations are imposed by conventional generating units and the limited size of the systems, [3,4]. For power system sizes beyond a few MW, pumped storage is the most technically mature and economically viable centralized storage technology, particularly suited for facilitating large scale RES integration in medium and large power systems, due to its high power and energy capacity, [1,2,5–9].

A favourable and realistic way to introduce pumped storage in island systems is based on the concept of hybrid power stations (HPS), which are virtual power plants, comprising wind farms (WFs) and storage facilities, operating in a coordinated manner, [10–12]. The basic concept is that wind energy, which would otherwise be discarded, due to the penetration limits imposed (e.g. during periods of low load and high wind), can be stored by pumping water to the upper reservoir. This energy is subsequently recovered in a controllable manner via the hydro turbines, permitting thus the substitution of thermal energy and capacity. Concerning the exploitation of available wind energy, besides pumping, there exists also the possibility of partially substituting dispatched hydro generation (*Hydro-Wind* mode of operation). As shown in Refs. [10,12–14], HPS projects can constitute attractive investments, while from a system perspective, the integration of a properly sized HPS may lead to the reduction of the island system levelized cost of energy (LCOE), [14].

The introduction of wind-pumped-storage HPS for increasing wind energy penetration levels has been the subject of several publications, where operating concepts, expected benefits and sizing issues are discussed, [10–20]. However, the published research on HPS dynamics and their effect on the transient response of power systems they are integrated into, is clearly insufficient, focussing actually on the dynamics of individual HPS components. Specifically, extensive work has been performed on hydro power stations, e.g. Refs. [21–26], as well as on wind turbines (WTs), e.g. Refs. [27–30], covering all aspects of modelling, control and system integration. On the other hand, limited material has been published on pumped storage plant dynamic analysis and system integration aspects. A simplified and a more accurate model of the hydraulic part of a pump are presented in Refs. [24,25] respectively, while in Ref. [26] the transient behaviour of reversible pump-turbine units is investigated. The potential contribution of pumped storage in alleviating frequency regulation problems in systems with high wind penetration is discussed in Refs. [31,32]. An investigation of the dynamic response of autonomous power systems incorporating wind-pumped-storage HPS is presented in

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Ref. [33]. Although this paper addresses the issue in an consistent manner, it does not investigate the effect of all HPS operating modes, while the analysis is performed for large island systems, employing conventional generating units with a slower response compared to hydro turbines (like steam turbines and combined cycle plants), therefore the substitution of conventional units by hydro turbines is expected to have a positive effect on system dynamics.

In this paper the effect from the integration of wind-pumped-storage HPS on the dynamic behaviour and stability of autonomous power systems, as those existing on small and medium sized non-interconnected islands, is systematically investigated. Technical issues associated with the various HPS operating modes are discussed, including the substitution of conventional diesel units by hydro turbines, the combined wind-hydro generating mode and the coordination of wind and pumping facilities. In all cases the focus is on the dynamic response of the HPS components and the system in total, rather than on energy efficiency and economic viability issues, which have been the subject of other publications (e.g. Refs. [10–14]). The objective is to assess the effect from the introduction of pumped storage facilities on the dynamics of small isolated power systems, identify possible constraints regarding the operation of the HPS and investigate and propose solutions. A realistic non-interconnected island system and an indicative HPS are used as study case in the paper. All simulations have been performed using DigSilent/PowerFactory, [34].

The paper is organized as follows. In Section 2, the study case island system and HPS are described. The dynamic models used for the components of the system are outlined in Section 3. Simulation results from the analysis of the system response with and without the HPS, at the different possible operating modes, are presented in Section 4. The main conclusions are summarized in Section 5.

2. Description of the study-case system

A representative medium-sized-island system, shown in Fig. 1, is used as study case. The island generation system consists of conventional thermal units (diesel units) and renewable power stations (WFs and an HPS). A small 150 kV transmission network feeds two 150/21 kV substations (S/S) and their 20 kV distribution network. Analytically, the island system relies on a conventional Autonomous Power Station (APS), comprising 7 × 15 MW internal combustion diesel engines, which supply the two main S/S via three overhead high-voltage (HV) 150 kV lines. The total installed WF capacity is 14.5 MW. The five WFs of the island are all connected to the medium voltage (MV) 20 kV distribution network and comprise several WT types. A single HPS is integrated in the island system, whose components have been sized based on [14,18,19]. It includes a 9 × 2 MW WF (WTs with synchronous generators and full-power converters), a pump station with 12 × 1.47 MW variable speed pump units and a hydroelectric plant with 3 × 5 MW turbines. The HPS is connected to the 150 kV system via a dedicated MV/HV substation and a radial HV line.

The integration of a relatively large HPS in an isolated island system raises several technical issues, including the following, to be further investigated in this paper:

- Hydro turbines are dispatched by the Island System Operator on a daily basis, typically at medium and high load hours, substituting expensive conventional units (in this paper, diesel generators). An important issue is whether the hydro turbines match the dynamic response characteristics of the substituted thermal units.
- During operation of hydro turbines, part of their dispatched output power may be substituted by the power generated by the HPS WF (*Hydro-Wind mode*). In such a case, the hydro turbines need to compensate for the high variability or potential loss of wind power.
- In a saturated island system, wind power generated by the HPS WF is primarily stored by pumping action (*Wind-Pumping mode*), rather than fed directly to the load [10–12]. In this mode, the pumps need to effectively track wind power variations.
- The island system will operate at substantially higher wind penetration levels, placing an increased frequency regulation

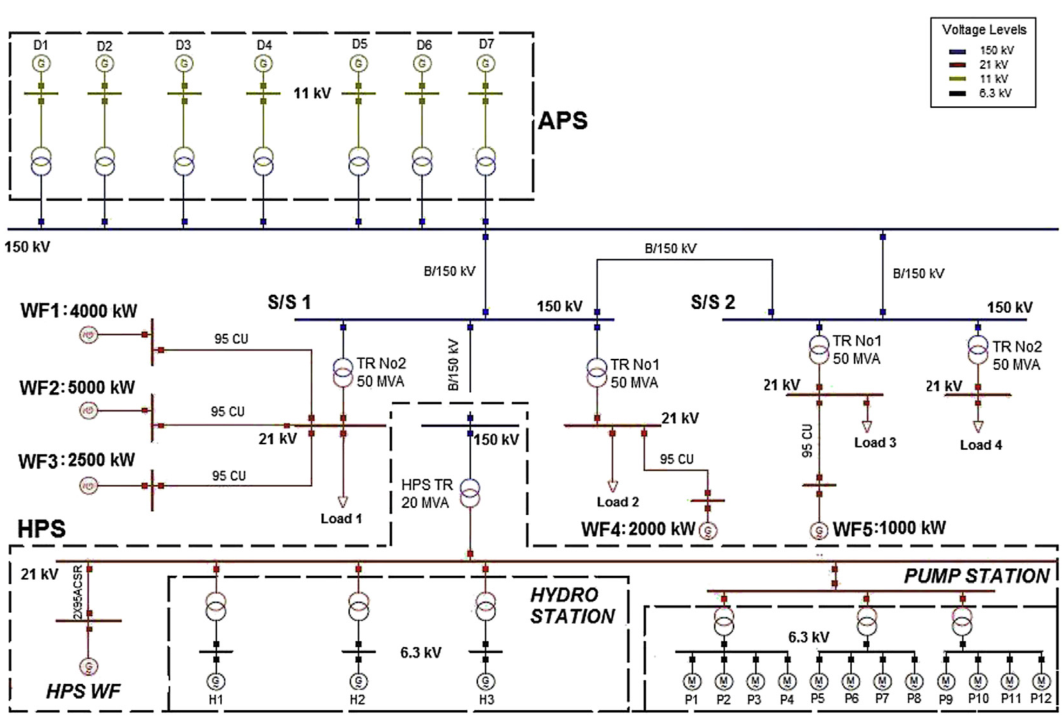

Fig. 1. Simplified single line diagram of the examined island power system.