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Stability of autonomous power systems with reversible hydro power plants
A study case for large scale renewables integration

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A B S T R A C T

This paper addresses the dynamic stability analysis of an islanded power system regarding the installation of a reversible hydro power plant for increasing renewable energy integration. Being a high-head facility, the hydro power plant consists of separated pumps and turbines (Pelton type). In order to properly support the identification of hydro pumps connection requirements and the technology to be used, different options were taken into consideration, namely: fixed speed pumps coupled to induction machines directly connected to the grid and adjustable speed pumps supplied by a drive system. Extensive numerical simulations of the power system's dynamic behaviour response allowed the evaluation of the hydro power plant's role for the purpose of grid stability conditions. These simulations showed that the high-head hydro power installation provides a marginal contribution to system frequency regulation when explored in turbine operation mode, leading to a reversible power station with a single penstock. Moreover, due to the significant additional system load introduced by the hydro pumping units, the obtained results clearly indicate that supplementary regulation flexibility is required to attend the need of assuring the stable operation of the system in case of critical disturbances such as grid faults. The study case demonstrates that, although the foreseen operation of a reversible hydro power plant creates new security challenges to overcome in an autonomous power system, robust technical solutions can be identified without increasing, from the local system operator's perspective, the operation complexity of the power system.

1. Introduction

Increasing the share of renewable energy sources in islanded power systems has been one of the most relevant challenges in the recent times. This challenge is aligned with the goal of significantly reducing the dominance of conventional thermal-based generation units due to economic and environmental concerns. However, integrating non-synchronous and time variable renewable generation, such as wind power, brings additional difficulties due to the need of ensuring adequate power-frequency regulation capability, which is traditionally provided by diesel-based synchronous units. In scenarios with increasing shares of renewable energy sources, the operational requirements of diesel power plants, together with spinning reserve criteria typically set by local system operators, are likely to lead to renewable energy curtailment, especially during valley hours. In order to overcome renewable energy curtailment, energy-storage-based solutions must be adopted. Depending on specific characteristics of the system, as well as on the volume of energy that is to be stored, the technological solutions for energy storage rely in electrochemical batteries or reversible hydro power plants [1–7].

While the advantages granted by large-scale integration of renewable power are evident, the technical conditions that assure system security must be preserved. As identified in Ref. [6], the large-scale integration of wind power in isolated power networks leads to the need for a careful review of the spinning reserve criteria in order to maintain the supply-demand balance. In line with the spinning reserve criteria, one of the main factors associated to dynamic security in isolated power systems is the response time of the active primary frequency control systems following a disturbance such as a sudden generation unit tripping. The reaction

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time of the generation units in charge of the frequency regulation is therefore crucial in order to avoid load shedding [6].

The ability to provide fast power-frequency control is consequently one of the relevant features of battery-based energy storage solutions for autonomous power systems with high load-generation variability [8]. Following this rational, a methodology for sizing a battery energy storage system is presented in Ref. [9], taking into account both inertia response and fast frequency regulation capabilities. However, when large-scale renewable energy sources integration in autonomous power systems requires significant volumes of energy transfers from valley to peak hours, battery-based solutions become economically less interesting, considering the higher costs per unit of energy storage capacity [10]. In this case, technical solutions based on the proper sizing of reversible hydro power plants – usually equipped with separated pumps and turbines – can be exploited in physical locations with adequate conditions for its construction [11–13].

The construction of reversible hydro power plants typically involves artificial reservoirs, only feasible in islands with appropriated orographic and climatic conditions. The round-trip efficiencies and the larger storage capacity of these power plants are important characteristics for the relevance of its exploitation in large-scale energy storage applications. Therefore, reversible hydro power plants are regarded as the most technically mature and economically viable alternative for power system sizes of a few MW and beyond [14]. Nevertheless, the dynamic performance of a solution as such is crucial for assuring system stability. In Ref. [13], the concept of no-flow operation of Pelton turbines within a reversible hydro power plant is explored in order to provide adequate spinning reserve and frequency regulation capability in autonomous power systems. The authors identify the need of installing hydro turbines with appropriate inertia time constants, as well as the construction of separate penstocks — one for the pumps and another one for the turbines. However, the authors limit the scope of their approach to the load-following performance of the hydro power station, neglecting the stability conditions of the system following critical events such as grid faults. The dynamic performance of an islanded power system with a wind-pumped-storage station is addressed in Ref. [15], where these authors also describe the use of a reversible hydro power plant equipped with two penstocks (one for the pumps and other one for the turbines). These authors consider that power-frequency control capabilities are available in both wind generators and pumping units, which are connected to the grid through a full-scale frequency converter. The analysis of system operation is based on medium load scenarios, while scenarios with the large increased share of renewables such as like valley load operational conditions are not considered, diminishing the robustness of the proposed solution. A distinctive feature of the two previously referred works relies on the use of separate penstocks for pumps and turbines. Although it requires a higher investment, it makes possible to simultaneously operate pumps and turbines (especially during valley hours), allowing hydro turbines to have an active role on the provision of power-frequency regulation under any circumstances.

In this paper, the stability constraints arising in a real isolated power system from a medium-size island located in the European Atlantic Ocean are addressed, aiming to define the main technical requirements to be considered in the reversible hydro power plant foreseen for installation, to increase renewable energy integration. Regarding system stability as defined by the local system operator, it is required to maintain a minimum number of two diesel generation units in the system during all load conditions. The relevance of the presented approach, in contrast to previous works, relies on the demonstration that robust operation can be achieved in extreme operating scenarios while resorting to a single penstock. With respect to system operation, this critical feature of the system does not allow for the simultaneous operation of turbines and pumps. Additionally, within the scope of having possible solutions for the hydraulic pumps grid connection (either fixed speed pumps mechanically driven by squirrel cage induction machines directly connected to the grid or variable speed pumps mechanically driven by induction machines connected to the grid through a full scale frequency converter), it is also demonstrated that robust solutions can be achieved regardless the technology that is chosen.

The global organisation of the paper is structured as follows: initially, the adopted stability study formulation is presented in Section 2; afterwards, Section 3 describes the study case and the analysis of simulation results obtained for the considered real power system; finally, Section 4 presents the main conclusions from the performed analysis.

2. Stability study formulation

In islanded power systems, ensuring system security and robustness is usually associated to the need of avoiding load shedding occurrence as a consequence of excessive frequency deviations [6]. Therefore, in the stability study formulation, the following security criterion is adopted: the system is considered to be secure if *none of the foreseen disturbances lead to automatic under-frequency load shedding situations*.

In order to perform a robust security analysis, the foreseen set of disturbances for which security must be assured usually comprises: (a) *N-1 contingencies*, such as a generation unit sudden loss; (b) *three-phase short-circuits*, located in one of the transmission lines or distribution feeders, leading to the disconnection of the line/feeder as a result of fault clearance by the protection system. In these particular cases, the fault-ride-through behaviour of converter-interfaced units (being either renewable energy sources or hydro pumps connected to the grid through a drive system), as well as the subsequent post-fault response (e.g. active power ramp-up), has a significant impact on the system power-frequency regulation.

In order to assure system security for the possible range of power system operating conditions, a worst-case-based approach is envisioned, leading to the definition of extreme operating scenarios to be evaluated, namely: (a) a valley hour scenario with maximum pumping power and maximum renewable power generation integrated in the system; (b) a higher-load scenario with maximum renewable power generation (without the use of pumping units, but including the hydro power production provided by the Pelton turbines).

In the extreme valley scenario, the hydro pumps are assumed to be connected at rated power, in order to maximise renewable power production without violating the technical constraints of thermal generation units (i.e., minimum number of connected units and spinning reserve criteria). This valley scenario provides the extreme conditions in terms of having sufficient: (a) *thermal positive spinning reserve, after a power unit loss*; (b) *negative spinning reserve for the sudden loss of fixed speed pumping units and the temporary load decrease of variable speed pumping units, after a short-circuit*.

Regarding the aforementioned valley scenario, the power-frequency regulation capabilities of the system are critical for assuring system stability and security. The provision of power-frequency regulation from the reversible hydro power plant requires the use of Pelton turbines in the no-flow operation mode at the same time that pumping units are in service. Such technical solution allows reducing the time required for Pelton turbines to inject power into the grid and to improve global system inertia. In this case, its generator is synchronized with the power system, being operated in a synchronous condenser mode (i.e., performing