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Contribution of a hydraulic short-circuit pumped-storage power plant to the load–frequency regulation of an isolated power system

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ABSTRACT

In this paper, the contribution of a hydraulic short-circuit pumped-storage power plant (HSCPSPP) to the load–frequency regulation (LFR) of an isolated power system has been further analyzed by means of simulations. For this purpose, a simulation model has been developed that considers the AGC system and both the synchronized thermal units' and the HSCPSPP's response to frequency deviations and power set-point signals sent by the AGC system. The frequency deviation of the power system and the electromechanical behavior of the HSCPSPP have been modeled by using commonly accepted approaches for studies on long-term dynamics of power systems. The behavior of the penstock has been considered through an elastic water column model. The simulations results demonstrate that the HSCPSPP has a large flexibility and that can contribute to a great extent to the LFR of the system, while fulfilling the requirements established by the TSO and preserving the plant safety.

Introduction

During the last decade, the increase in the penetration of wind energy into the majority of electric power systems has aroused the interest on pumped storage power plants (PSPP) as a means of helping to integrate wind power into the grid in an efficient and reliable manner as shown in several studies [1,2].

Special interest is being gained by non-conventional PSPP such as those using variable speed technologies [3,4] and hydraulic short-circuit pumped-storage power plants (HSCPSPP) (i.e. PSPP operating in hydraulic short-circuit mode), mainly due to their capability for providing LFR both in generating and pumping or consumption modes. This paper is aimed at analyzing in detail the contribution of a HSCPSPP to the LFR of an isolated power system by means of simulations.

To authors' knowledge, the only HSCPSPP currently in operation is Kops II power plant. It is composed of three ternary units, each comprising one Pelton turbine connected through a lock-up clutch to a pump, both coupled to a synchronous machine. Thanks to the clutch, each unit can operate simultaneously in pumping and generating mode; in this way, the power plant can be "seen" by the grid as a controllable load, with a power regulation range equal to that of the Pelton turbines in operation [5–7]. Hereinafter, the terms "generating mode" and "consumption mode" will be used to refer to the cases where the net electric power delivered to the grid is positive and negative, respectively, regardless the number of turbine and pump units in operation.

Among the advantages of this particular scheme, the operational flexibility is currently the most important one in relation to the LFR of the power system [8]. Nevertheless, there are very few works where the contribution of a HSPCPSPP to the LFR of a power system has been assessed [4,9]. The system modeled in [4,9] comprises thermal and wind power generation as well as one HSCPSPP. The dynamic behavior of the three generation sources is modeled with a high level of detail. Two different cases were analyzed in each of these papers. In [9], authors analyze the contribution of a HSCPSPP to compensating an increase in wind power and a wind farm shut down. In both cases, the pumped-storage power plant is initially operating in hydraulic short-circuit mode. In the first case, the increase in wind power is compensated by the turbine, whereas in the second case the wind farm shut down is compensated by the pump shut down. In [4], authors analyze the contribution of a HSCPSPP to compensating a step load acceptance and a decrease in wind power. In both cases, the pumped-storage power plant is initially operating in hydraulic short circuit mode and the change in wind power is compensated by the turbine. In neither of these papers, the AGC system and, therefore, the contribution of thermal units to the secondary LFR were considered. In [4], the hydraulic short-circuit scheme is compared with a variable speed pumped storage unit.

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The main contributions of this paper with respect to [4,9] are as follows. The synchronized thermal units and the HSCPSPP are assumed to be connected to an automatic generation control (AGC) system. The AGC system and the response of the synchronized units to power set-point signals sent by the AGC system are conveniently modeled. A total of twenty-four cases are analyzed in order to fully characterize the HSCPSPP response. Twelve cases correspond to situations where the HSCPSPP would be requested to provide primary and secondary LFR (spinning reserve); in these cases, different participation factors of the synchronized units in the secondary LFR are considered, in order to highlight the capability of the HSCPSPP for providing secondary LFR. Eleven cases represent different start-up and shut-down maneuvers, that could be carried out by request of the TSO for providing LFR (non-spinning reserve), as a consequence of the "inter-hourly" difference in the power operation schedule or in an emergency situation. In one case, the participation of the HSCPSPP in the load-shedding scheme of the system is analyzed. Large hydraulic transients that could appear in the HSCPSPP as a consequence of the start-up or shut-down of any generating or pumping unit are analyzed in last twelve cases. In this way, it is intended to study the contribution of the HSCPSPP to the LFR of an isolated power system from the point of view of both the transmission system operator (TSO) and the power plant owner. For this purpose, an extensive simulations campaign was carried out in such a way that the most severe (load or generation) tripping events that could occur both in the power system and the HSCPSPP were covered, and that it was possible to fully characterize the response of the HSCPSPP in terms of both electrical and hydraulic magnitudes.

The AGC system is in charge of restoring the system frequency and reestablishing the power exchanges between areas to their scheduled values after any unexpected unbalance between generation and demand [10,11]. For these purposes, the AGC system computes almost continuously the so-called *area control error* (ACE), as a function of both the frequency and power exchange errors, and generates and sends control signals to the synchronized units with the aim of eliminating the above-mentioned ACE. In isolated power systems, such as the one analyzed in the paper, the AGC system is in charge "only" of bringing the system frequency back to its nominal value; ACE and control signals are computed and generated consistently with such purpose [12].

In order to study whether or not a power plant helps to improve the LFR of the system it is therefore important to take into account the system response criteria established by the TSO [13] and to model with sufficient accuracy the LFR response of the entire system. For this purpose, it is necessary to model the units' response to both frequency deviations and power set-point signals sent by the corresponding automatic generation control (AGC) system [14].

From the perspective of the plant owner, it is important to guarantee that the plant's response meets the criteria established for providing LFR, as well as the security of the plant during LFR maneuvers [15]. In the case of a HSCPSPP, it implies to analyze the plant's response to sudden variations in the wicket gates opening, motivated either by a fast frequency deviation or a change in the power set-point; additionally, it is necessary to study the plant's response to start-up and shut-down maneuvers.

There are many references in the technical literature where the response to frequency deviations of different types of generating units has been modeled with diverse degrees of detail [16,17]. Nevertheless, authors agree with [18] that "a certain mix up is found in these references regarding the necessary elements to correctly model a generating unit for AGC purposes". Actually, to authors' knowledge, in most of the published works the influence of the AGC system is neglected; the emphasis is put on the first 25–50 s after the corresponding tripping or fault event [19].

There are also quite a few references where the response of a conventional hydropower plant (HPP) or a PSPP to both power set-point variations and frequency deviations, has been analyzed from different indicators. In some of these references, the analysis is carried out assuming that the power plant is uncoupled from the power system or connected to an infinite bus [20], whereas in others, the influence of the power system frequency response is considered with diverse degrees of detail [21]; but no reference has been found where the influence of the AGC system on both the HPP and the rest of the power system's generating units has been explicitly considered.

The paper is organized as follows. In section 'Description of the HSCPSPP and the power system', main characteristics of the HSCPSPP and power system where the study has been carried out are presented. In section 'Simulation model', the simulation model developed for the purposes of the paper is described in detail. In section 'Simulations', all simulations carried out are listed and classified according to the conclusions or results expected to be obtained from each of them. In section 'Discussion of results', the obtained results are further discussed. Finally, in section 'Conclusion', main conclusions of the paper are duly drawn.

Description of the HSCPSPP and the power system

The considered HSCPSPP is currently in the pre-planning stage and is expected to be installed in one of the Spanish insular electric power systems. The total installed power of thermal generation in July 2012 was 852 MW. The system comprises 6 fuel-oil generating units, 5 diesel-oil generating units, 7 gas-oil generating units and 2 combined cycle gas units.

The HSCPSPP analyzed in this paper is different from the scheme implemented in the Kops II plant. Pumping and generating units are located within two different buildings, hereinafter referred to as pump and hydropower stations, respectively; each pump and turbine is coupled to a different synchronous machine. The hydropower station comprises two 60 MW Pelton generating units, whereas the pump station comprises four 30 MW multistage pumping units. Water is conveyed between the upper and lower reservoirs through a single penstock; the scheme includes neither a head-race tunnel nor a surge tank. Numerical values as well as a brief description of all parameters used in the following section are included in the Appendix. All design parameters were taken from the plant pre-feasibility study. It is important to note that HSCPSPP hydraulic design corresponds to an installed power twice the above-mentioned values, due to limitations imposed by the existing transmission network capability; an extension of said capability is foreseen for the next future.

Simulation model

The block diagram of the simulation model developed in Matlab–Simulink for said purpose can be seen in Fig. 1.

Conduits

Penstock

Mass and momentum conservation equations properly describe transient-state flows in closed conduits [22]. In this paper, a lumped parameters approach (i.e. a finite difference method) has been used to solve these equations. This approach leads to a system of ordinary differential equations that can be represented as a series of Γ-shaped consecutive elements of length L_e. The "orientation" of the Γ-shaped elements may vary according to the upstream and downstream boundary conditions of the pipe. A scheme of the model can be seen in Fig. 2. In this case these boundary conditions are given by