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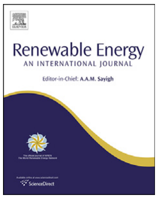

Power-frequency control of hydropower plants with long penstocks in isolated systems with wind generation

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ABSTRACT

In this paper the power-frequency control of hydropower plants with long penstocks is addressed. In such configuration the effects of pressure waves cannot be neglected and therefore commonly used criteria for adjustment of PID governors would not be appropriate. A second-order Π model of the turbine-penstock based on a lumped parameter approach is considered. A correction factor is introduced in order to approximate the model frequency response to the continuous case in the frequency interval of interest. Using this model, several criteria are analysed for adjusting the PI governor of a hydropower plant operating in an isolated system. Practical criteria for adjusting the PI governor are given. The results are applied to a real case of a small island where the objective is to achieve a generation 100% renewable (wind and hydro). Frequency control is supposed to be provided exclusively by the hydropower plant. It is verified that the usual criterion for tuning the PI controller of isolated hydro plants gives poor results. However, with the new proposed adjustment, the time response is considerably improved.

1. Introduction

In last years, the use of renewable energy sources to displace fossil fuels in small isolated systems has received considerable attention [1–4]. Many islands have an excellent local wind potential so that economic and environmental costs of fuels may be avoided. Although these sources can contribute to some extent to power-frequency regulation, in many cases this service is provided mainly by conventional power plants. Hydropower plants can assume advantageously this task due to its renewable character. Moreover pumped storage schemes compensate uncertainty in wind production. This type of solution is usually named "combined wind-hydro generation".

The use of PID governors in hydropower plants is a common practice [5] and suitable criteria for gain adjustment have been thoroughly studied in last decades [6–11]. However the hydropower plant configurations found in the systems mentioned above may include substantial differences with respect to general cases. Specifically, the length of the penstock can be considerably large due to special topographic conditions. This circumstance limits the applicability of the rigid-water-column models [12] and the PID adjustment criteria based on this assumption [13,14].

Although several contributions have been described to modelling the dynamic response of hydropower plants, when the influence of pressure waves cannot be neglected [15–19] very few attempts have been found in the literature dealing with the adjustment of gains of the PID governor in such cases. It is worth mentioning the work presented in Ref. [20] where the stability boundaries in terms of the PI gains are determined under the influence of the water column elasticity, extending the results obtained for rigid water column. In Ref. [21] a methodology based on a reference model is proposed to obtain a PID governor gains; the turbine-penstock is represented by a synthesized second order model [13]. In Ref. [17] the PID parameters determination is based on a high order plant model, where the turbine transfer function is identified by means of time-domain simulations.

The work of [8,22–25] is aimed to obtain simple rules, recommendations or expressions useful for the PID governor tuning in the plant predesign phase, but they do not include water elasticity effects. For this purpose Classic Control tools and techniques, (root locus plot, bode diagram,...) have been successfully applied.

In this paper, a methodology is presented to achieve a similar objective taking into account water elasticity effects. For this purpose, a simplified linearized model is proposed to define some

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practical tuning criteria for a PI governor by pole placement method [22]. The model is based in a lumped parameters approach [16,26] adjusted to match the penstock frequency response in the range of interest.

The controller performance is evaluated from the plant dynamic response obtained by simulation, using a detailed model which includes nonlinearities and distributed elasticity effects. The proposed PI adjustment criteria are tested in a real system implemented in a small island where the generation is provided by a wind farm and a hydropower plant [3,27]; the frequency is supposed to be controlled only by the hydropower plant.

Although modern wind generators could contribute to frequency regulation through pitch control, this contribution entails a cost: some wind energy will be lost [28]. So, in this paper no contribution to frequency regulation from the wind farm is assumed.

The paper is organized as follows. In Section 2 the hydro plant dynamic model is described and a preliminary assessment of elasticity effects is done using three reference power plants. In Section 3 the applicability of a reduced order model for stability analysis is discussed. In Section 4 two tuning criteria are formulated using the reduced order model and their performance is analysed. In Section 5 the obtained results are tested in a real hydropower plant: Gorona del Viento in El Hierro (Canary Islands). Finally, in Section 6, main conclusions of the paper are duly drawn.

2. Modelling

Assuming that a hydroelectric plant operates in an isolated system, which includes wind generation and resistive loads, the block diagram of its dynamic model is shown in Fig. 1.

The equations associated with each block are detailed below. All variables, coefficients and parameters which appear in the expressions are described in the Appendix 1. In particular, p_d represents the net demand to be supplied by the hydro plant.

2.1. Penstock

In order to consider the elasticity of water and conduit, the expression (1) is used [14].

$$\frac{\Delta \mathrm{H(s)}}{\Delta \mathrm{Q(s)}} = -\frac{\mathrm{T_w}\frac{\mathrm{a_w}}{\mathrm{L}}\left(1-\mathrm{e}^{-2\frac{\mathrm{L}}{\mathrm{a_w}}\mathrm{s}}\right)}{\left(1+\mathrm{e}^{-2\frac{\mathrm{L}}{\mathrm{a_w}}\mathrm{s}}\right)} \quad \text{where} \quad T_w = \frac{L}{gF}\,\frac{Q_b}{H_b} \tag{1}$$

For the sake of accuracy the head losses, local (k_{loc}) and continuous ($r/2$), are included as shown in Fig. 2 [15]. The net head h, is obtained from the reservoir water level hc^0, considering the friction losses and the pressure waves contribution.

2.2. Turbine

The Equation (2) [15] gives the relationship between p.u. values of flow q, head h and nozzle opening z.

$$q = z\sqrt{h} \tag{2}$$

As is frequently the case in hydropower plants with long penstocks located in islands, Pelton turbines will be considered. The expression (3) used for p.u. shaft torque corresponds to ideal rated conditions, where the absolute fluid speed is twice the runner peripheral speed [29].

$$c = q\left(2\sqrt{h} - n\right) \tag{3}$$

The modelled power plant may have two or more identical units, which are supposed to work at the same operating point; thus a single equivalent turbine has been considered.

2.3. Generation – load

Equation (4) represents unit dynamics in the time range of interest, where only inertial effects are relevant [10,30].

$$c - c_d - k\Delta n = T_m\frac{dn}{dt} \tag{4}$$

As mentioned in the Introduction, the considered hydro power plant is connected to an isolated system with wind generation; then c_d represents the p.u. net load torque at reference frequency, $n_r = 1$ p.u. Input variable $p_d = c_d$ p.u. (see Fig. 1) is modified as a result of a variation in the loads connected to the system or a change in the energy supplied by the wind farm. Inertia parameter T_m refers only to the hydro plant as wind generators are supposed to be connected to the system through frequency converters. The parameter k accounts for the load sensitivity to frequency, as wind generation does not contribute to frequency regulation.

2.4. PI controller

A conventional proportional-integral (PI) controller processes the frequency error signal: $(n_r - n) - \sigma\Delta z$. Equation (5) gives the changes in the turbine nozzles due to the controller action.

$$\Delta z = \left[\frac{1}{\delta} + \frac{1}{\delta T_r}\int dt\right]\left[(n_r - n) - \sigma\Delta z\right]; \quad K_P = \frac{1}{\delta} \text{ and } K_I = \frac{1}{\delta T_r} \tag{5}$$

In the case considered, the frequency control is carried out only by the hydro plant; then, the permanent speed droop σ is set to zero and the frequency set-point n_r remains constant.

2.5. Example. Reference power plants

The importance of elasticity effects is assessed using three reference hydropower plants with different penstock lengths, the PI governor being tuned according to the recommendations given in Ref. [11] for an isolated plant without considering the elasticity of water and conduit. The main characteristics of the reference power plants are summarized in the Table 1.

As may be appreciated in the table, the three proposed reference plants differ substantially in the values of the Allievi parameter $\rho = a_w\, v/2\, gH$. In Ref. [12] the influence of the Allievi parameter on the stability of a hydro plant is studied, concluding that elasticity effects are important for $\rho < 1$. In Ref. [31] this limit is reduced to 0.75, warning that instability will appear when $\rho < 0.25$; in a

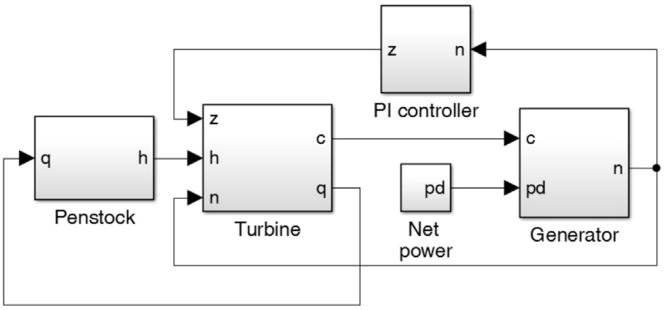

Fig. 1. Block diagram of the plant model.