Water level control system for a low-head run-of-river variable speed small hydropower plant

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Abstract: This paper presents part of the work carried out within the framework of a research project entitled *Application of variable speed and intelligent control technologies to hydropower generation*. Specifically, it is focused on the activities performed in order to achieve one of the main objectives of the project: the design of a water level control system for a low-head run-of-river variable speed small hydropower plant. A speed-based water level control system has been implemented in a laboratory plant and manages successfully to control the water level in the head pond. In addition, a model of the control system has been developed using Matlab-Simulink®, the validity of which has been verified by comparing experimental measurements with simulations results.

Keywords: Small hydropower, Run-of-river plants, Variable speed operation, Water level control.

1. Introduction

Due to its ability to quickly respond to short-term changes in electricity demand, hydropower plants, associated to reservoirs with enough storage capacity, are usually operated to supply variable power during periods of peak demand, thus providing the electric grid with operational flexibility and avoiding to some extent the power level variations in thermal plants. This operation scheme, referred to in the technical literature as *hydropeaking*, *hydroshifting* or simply *load-following*, can lead to fluctuating hydrologic patterns in the downstream river reach; furthermore, one should take into account that, high water releases during peak demand periods, are followed by a sharp decrease in these releases during off-peak periods in order to refill the reservoir and regain head. These fluctuations in water levels associated to peaking operation can cause considerable ecological damage to downstream river ecosystems.

Run-of-river operation allows following the natural flow pattern and, hence, it is becoming more and more frequent, to the extent that in several industrialized countries the corresponding regulatory authorities are reviewing or re-licensing hydropower projects and forcing them to change from peaking operation to run-of-river operation [1].

Run-of-river small hydro plants can not contribute significantly to load-frequency control of the electrical system; hence, instead of a conventional power-frequency control loop, a water level control loop is used in these cases [2] in order to adapt the water discharged through the turbines to the natural river flow. This requires monitoring the water level at the reservoir, or head pond, where the water intake is located, and adjusting the flow through the turbines in such a way that the level stays within certain pre-specified limits. Only few references are concerned with water level control in hydro plants [3].

Conventional hydro generating units either operate at the synchronous speed (synchronous generators) or deviate only slightly from the synchronous speed (induction generators). Therefore, in most cases the water level in the head pond is controlled by modifying the wicket gates opening. Kaplan turbines provide a very broad range of operating flows with considerably high efficiencies [4], thus being very suitable for low-head run-of-river hydro plants. However, there exists an increasing concern in many industrialised countries about the oil leakages due to the runner blades and wicket gates regulation mechanisms [5], which is resulting in several turbine design and refurbishment projects to eliminate oil from all turbine components (bearings and servomotors) [6], [7] to the extent that there have been several cases where double-regulated Kaplan turbines have been converted into single-regulated ones by welding the runner blades to the hub in a fixed position.

It is clear that single-regulated propeller turbines are more environmentally respectful than Kaplan turbines but, they present a narrower range of operating flows out of which the efficiency decreases rapidly [8].

Variable speed operation (VSO) allows changing the turbine speed in accordance with hydraulic conditions thus enlarging its operating range. It could therefore represent an alternative to the adjustable blades of Kaplan runners. VSO in small hydro plants has been recently tested in several European projects [9-11] where its technical feasibility was demonstrated. In regard to its economic feasibility, it must be properly assessed in each specific case since it depends on several different factors such as the power plant capacity or the variability of the site hydrological conditions, among others, and hence it is outside the scope of this paper.

In this paper, some of the activities carried out within the framework of a research project entitled *Application of variable speed and intelligent control technologies to hydropower generation* will be presented and discussed. Specifically, this paper is focused on the activities carried out in order to achieve one of the main objectives of the project: the *design of a water level control system for a low-head run-of-river variable speed small hydropower plant*.

2. Test bench measurements

First of all, an axial-flow propeller turbine with four adjustable guide vanes, directly coupled by a connecting shaft to an asynchronous generator, was placed on a test bench (Fig. 1). Several measurements were then carried out in order to evaluate the turbine performance under different operating conditions, namely: flow, net head, guide vanes position and running speed.

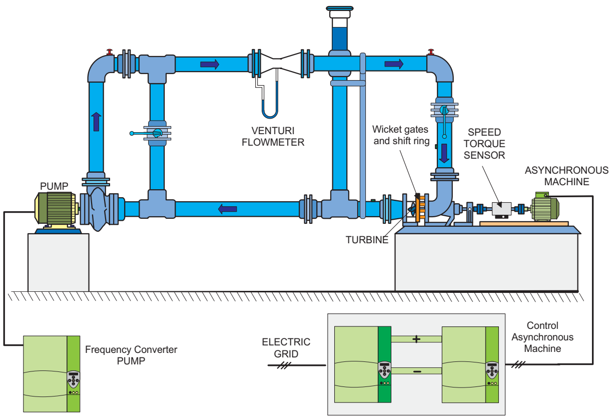

Fig 1. Test bench.

Head-discharge curves were obtained for several values of turbine speed and guide vanes position. In Fig. 2 the head-discharge curves for a fixed guide vanes position, α = 10º, are shown, when turbine speed is varied from 1000 to 2000 rpm. In turn, Fig. 3 shows the head-discharge curves for a fixed turbine speed value, n_t = 2000 rpm, when guide vanes position is varied from 0º to 20º.

From these figures, it can be observed that the regulation capability provided by the turbine speed was rather greater than that provided by the guide vanes position. Therefore, the former was selected as control variable to keep a constant water level in the head pond.

Furthermore, from measurements taken on the test bench and due to the nonlinearities observed in efficiency data, two artificial neural networks (ANNs) were trained in order to simulate the turbine behaviour and estimate the turbine efficiency [12].

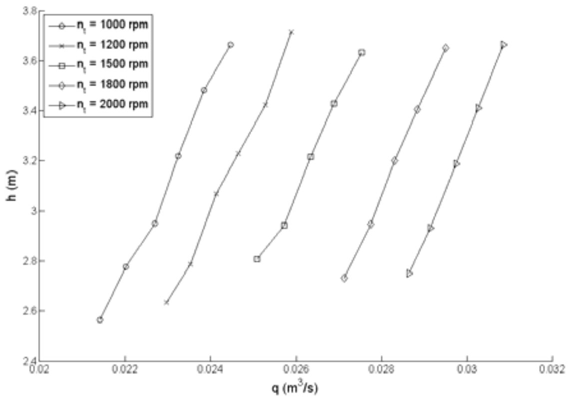

Fig. 2: Head-discharge curves for guide vanes position α = 10º.

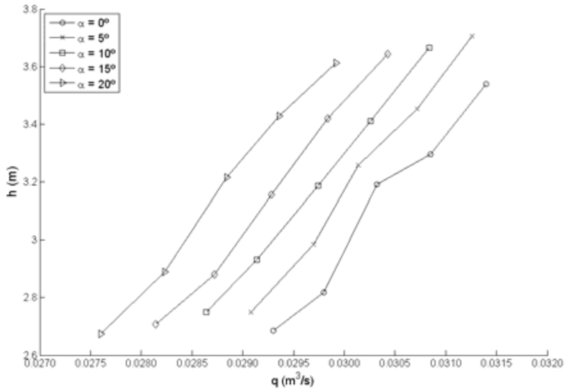

Fig. 3: Head-discharge curves for turbine speed n_t = 2000 rpm.

3. Experimental facility

The turbine generating unit was moved to a *laboratory plant*, the complete system being composed of: cylindrical water tank (playing the role of the head pond); head-race conduit; surge tank; penstock; turbine generating unit; and draft tube. The generator is connected to the AC grid through a regenerative frequency converter by means of which the turbine speed is conveniently modified. The guide vanes are connected to a shift ring, which is in turn coupled by a connecting rod to a circular bronze plate, driven by a servomotor. The water inflow to the tank is controlled with a variable-speed water pump, so that the plant operation under different river flow conditions can be studied. Fig. 4 shows the general layout of the laboratory plant.

4. Control system design

In order to undertake the design of the water level control system, the case of a dam-based hydro scheme was firstly considered. For this purpose, a model of the laboratory plant that ignores the influence of the surge tank (as if the

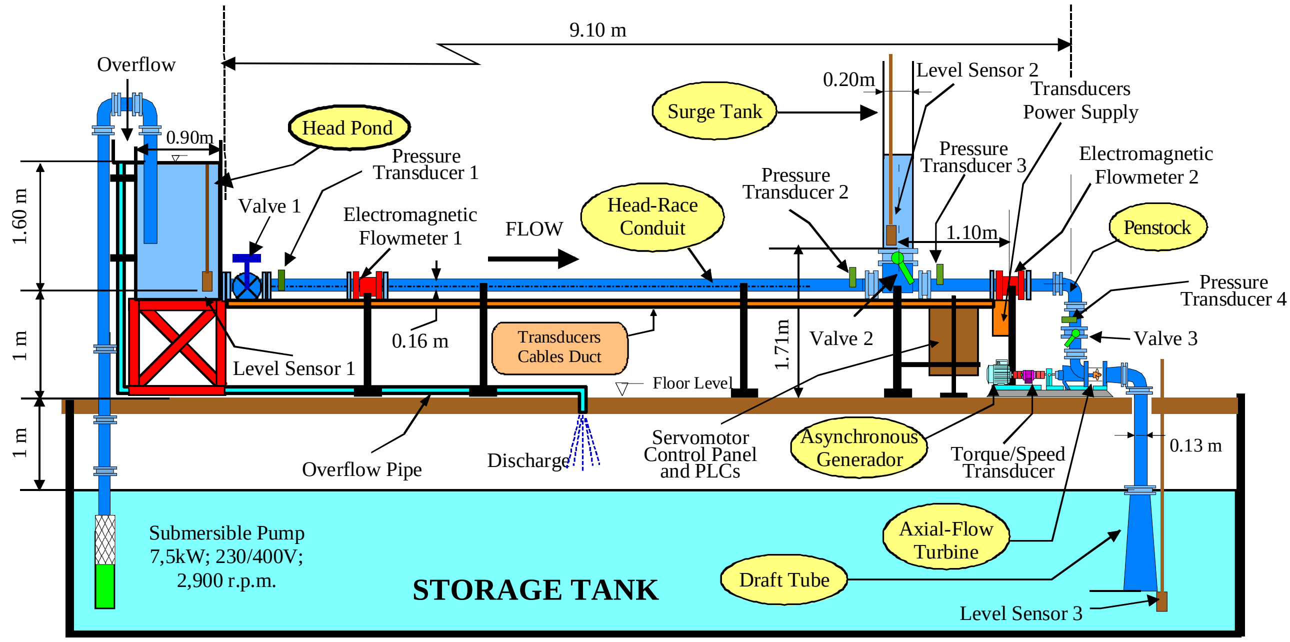

Fig 4: Laboratory plant layout

water inlet to the surge tank were closed by means of an appropriate flap valve) was developed in Matlab-Simulink®.

A control algorithm composed of two differentiated control loops was tested with the help of this model [12]. In the primary control loop, a conventional PI controller adequately tuned generates the necessary turbine speed to keep a constant water level in the head pond [13]. In the secondary control loop, once the water level has been stabilized, a maximum efficiency tracking algorithm chooses the guide vanes position that maximizes the turbine efficiency for the actual river flow using a look-up table. This action is done through a smooth transition, in order to avoid interfering with the primary control loop dynamics.

In order to fill in the look-up table, several simulations of the primary control loop were carried out, sweeping different combinations of river flow and guide vanes position. During each simulation, the river flow is varied whereas guide vanes position and water level reference remain constant.

ANNs trained from field measurements taken on the test bench were used to calculate the turbine net head and efficiency in simulations of both the primary control loop and the entire control system. The block diagram of the entire control system is shown in Fig. 5.

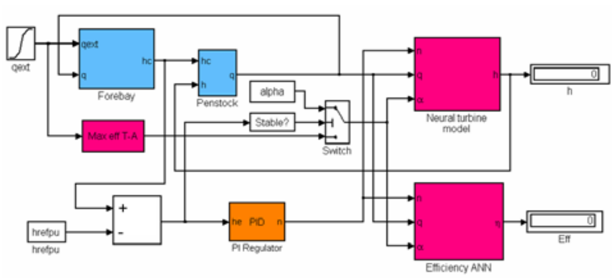

Fig. 5: Block diagram of the control system.

Several different smooth changes in water inflow to the tank were simulated in order to check the effectiveness of the system in controlling the water level in the head pond and whether or not the efficiency actually improved. The results of the simulations demonstrated that, indeed, it is possible to improve the turbine efficiency by adequately modifying the guide vanes position without losing head pond stability.

5. Laboratory plant commissioning

The laboratory plant was commissioned in summer 2007. The configuration of this plant (fig. 4) corresponds to a hydro plant with tunnel and surge tank. An open loop measurement campaign was carried out in order to estimate the head losses between the head pond and the turbine and other operational parameters. Least square fitting of the head losses measured in the head-race conduit can be seen in Fig. 6.

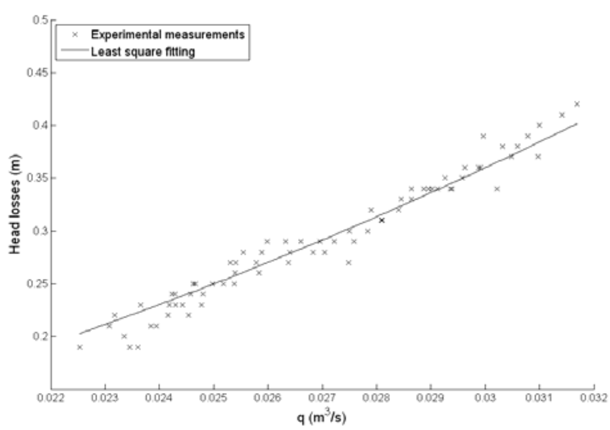

Fig. 6: Head losses in the head-race conduit.

After this measurement campaign, the above-mentioned primary control loop was implemented in the laboratory plant by means of a Siemens PLC S7-200 and three

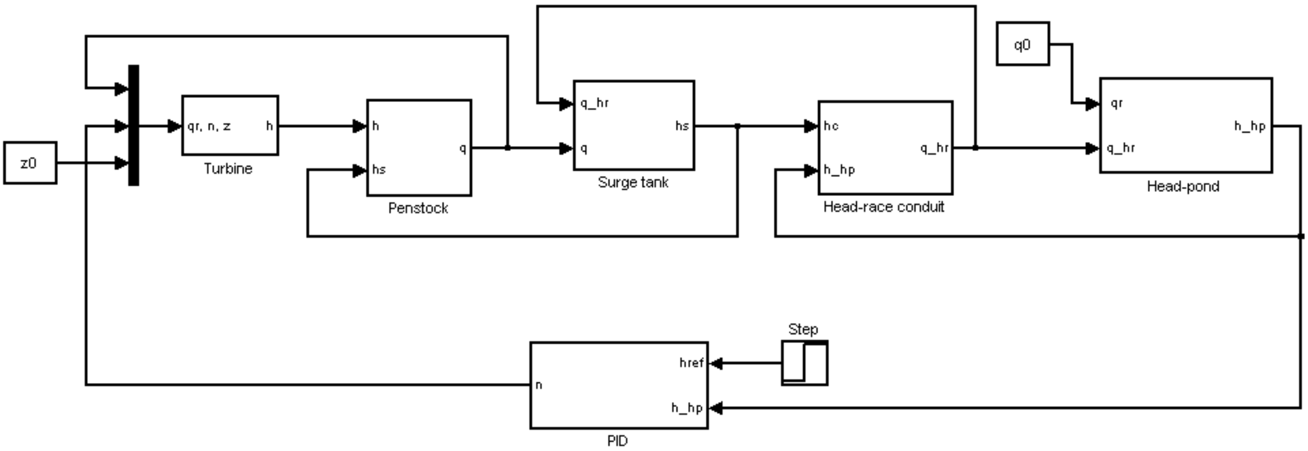

Fig. 7: Block diagram of the primary control loop.

analogue expansion modules EM 235, through which the plant automation is performed in a centralized manner. The configuration of the controller was performed using STEP 7 Micro/WIN programming software.

In parallel to the implementation of the primary control loop in the laboratory plant, a model of the control loop was developed also using Matlab-Simulink®. The block diagram of the model is shown in Fig. 7 and equations (1)-(5) model, respectively, the blocks head-race conduit, penstock, surge tank, head pond and turbine. Parameters b_{11}, b_{12} and b_{13} in equation (5) were obtained from the open loop measurement campaign.

$$\frac{dq_{hr}}{dt} = \frac{1}{T_{hr}}(h_{hp} - h_s - p_{hr}q_{hr}^2) \quad (1)$$

$$\frac{dq}{dt} = \frac{1}{T_p}(h_s - h - p_p q^2) \quad (2)$$

$$\frac{dh_s}{dt} = \frac{1}{T_s}(q_{hr} - q) \quad (3)$$

$$\frac{dh_{hp}}{dt} = \frac{1}{T_{hp}}(q_r - q_{hr}) \quad (4)$$

$$q = b_{11}h + b_{12}n + b_{13}z \quad (5)$$

Then, several closed loop tests were performed in the laboratory plant in order to study its dynamic response and check the validity of the Matlab-Simulink® model. Both proportional and proportional-integral control schemes were tested. Experimental measurements and simulation results were compared to each other, thus demonstrating the validity of the model. Figs. 8-11 show respectively experimental measurements and simulation results of the plant dynamic response to different step changes, Δh_{ref}, in the head pond reference level with both proportional (P) and proportional-integral (PI) control schemes.

As it can be seen in Figs. 9 and 11, there is a small initialization mismatch due mainly to the degree of data dispersion; it should be noted that the head losses and turbine coefficients were fitted from the above-mentioned open loop measurements data, some of which have a significant dispersion.

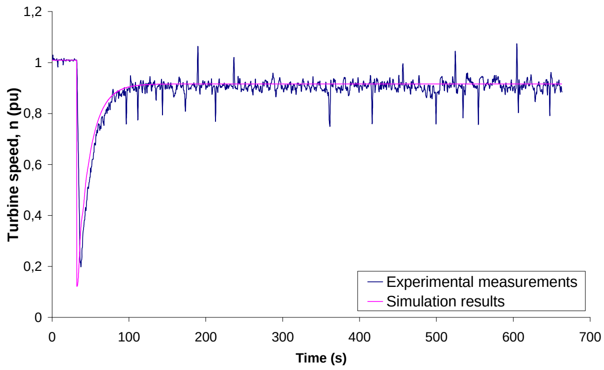

Fig. 8: Turbine speed with (P) control (Δh_{ref} = 0.080 pu).

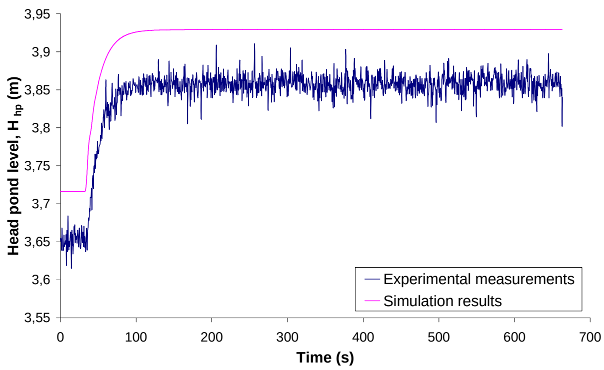

Fig. 9: Head pond level with (P) control (Δh_{ref} = 0.080 pu).

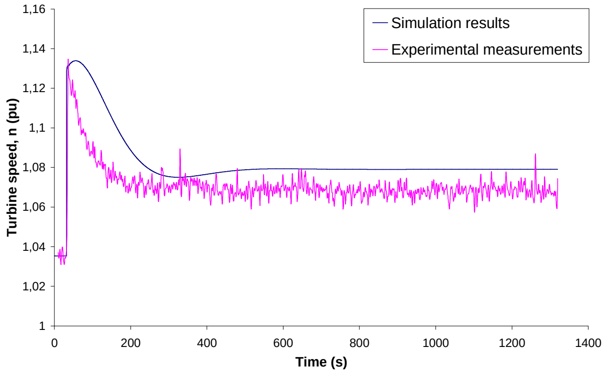

Fig. 10: Turbine speed with (PI) control (Δh_{ref} = - 0.033 pu).

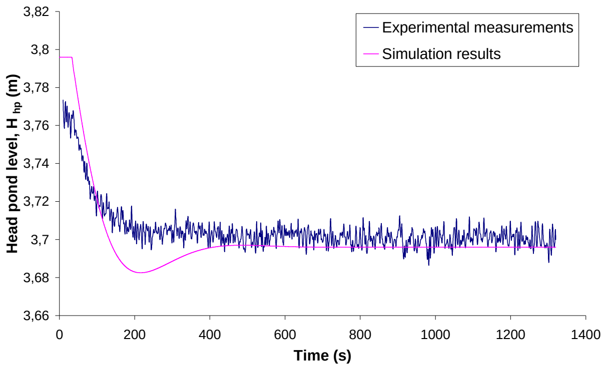

Fig. 11: Head pond level with (PI) control (Δh_{ref} = - 0.033 pu).

Once the plant hydraulic parameters were identified and the Matlab-Simulink® model was validated, a heuristic criterion presented in [14, 15] and based on the root locus method was used to adjust the controller parameters in the Matlab-Simulink® model. Unfortunately, the simulation results showed that the proposed criterion might cause the turbine speed to reach values out of the operating limits of the laboratory plant electromechanical drives (it should be noted that the heuristic criterion used was designed to control the water level in the head pond of a run-of-river hydro plant by means of the wicket gates, instead of the turbine speed). Therefore, the controller parameters were finally adjusted using the *auto-tuning* algorithm of Siemens PLC S7-200, which is based on the relay tuning method [16, 17].

Using the Routh-Hurwitz criterion, the *stability region* [16] of the laboratory plant was obtained as a function of the proportional and integral gains of the controller, and it was checked that parameters calculated by the auto-tuning algorithm were within the stability limits.

Next, a closed loop steady-state measurements campaign was carried out in order to fill in the look-up table where the secondary control loop should select, with a suitable search algorithm, the guide vanes position that generates the largest turbine efficiency for the actual river flow. Turbine speed and efficiency were measured for different combinations of water inflow to the tank and guide vanes position once steady-state had been reached; head pond reference level was kept constant during the entire measurements campaign. Figs. 12 and 13 show respectively all measurements of turbine speed and efficiency taken during this campaign.

Unfortunately, as it can be seen in Fig. 13, the turbine efficiency increases monotonically with the guide vanes position, probably because the small operating range of the laboratory plant; it should be noted that guide vanes position ranges from 0 to 20º. As a consequence of this measurements campaign, it was decided to discard the secondary control loop in the laboratory plant. However, the authors expect that in a hydro plant with a more realistic operating range, significant improvements in efficiency can be obtained by varying the guide vanes position. For that reason, as a continuation of the project, they are currently carrying out a study similar to that presented in [9] with data collected from a real hydro plant situated in a river basin in the northwestern area of Spain.

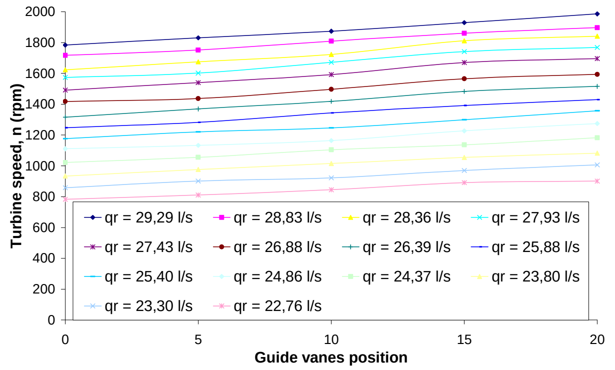

Fig. 12: Closed loop steady-state measurements (turbine speed).

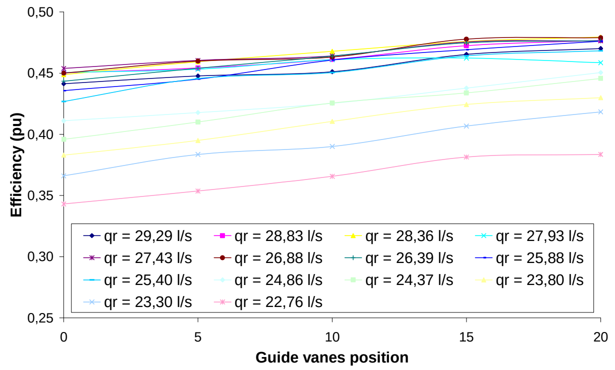

Fig. 13: Closed loop steady-state measurements (turbine efficiency).

6. Conclusions

The work carried out to design a water level control system for a low-head run-of-river variable speed small hydropower plant has been presented in this paper.

An experimental low-head run-of-river small hydro plant has been constructed and commissioned successfully in the Hydraulics Laboratory of the Technical University of Madrid. A *speed-based* water level control system has been implemented in the laboratory plant. The system successfully controls the water level in the head pond by means of a conventional PI controller that provides a regenerative frequency converter with the suitable turbine speed signal. This is an important milestone of the project since, to authors' knowledge, only one speed-based water level control system has been previously implemented in a different type of hydro plant [11].

Two ANNs were trained to reproduce the turbine behaviour (net head and efficiency) from measurements taken on a test bench during the first stages of the project. These ANNs were later used to design the water level control system of the plant.

In addition, a model of the control system implemented in the laboratory plant has been developed using Matlab-Simulink®, the validity of which has been verified by comparing experimental measurements with simulations results.

Appendix

The notation used throughout the paper is presented next:

b_{ij} Turbine coefficients.

h Net head (pu).

h_{hp} Water level in the head pond (pu).

h_s Water level in the surge tank (pu).

n Turbine running speed (pu).

p_{hr} Head losses coefficient in the head-race conduit (pu^{-1}).

p_p Head losses coefficient in the penstock (pu^{-1}).

q Water flow in the penstock (pu).

q_{hr} Water flow in the head-race conduit (pu).

q_r Water inflow to the tank (pu).

T_{hp} Water time constant of the head pond (s).

T_{hr} Water starting time in the head race-conduit (s).

T_p Water starting time in the penstock (s).

T_s Water time constant of the surge tank (s).

z Guide vanes position (pu).

Acknowledgments

This work was supported by the Spanish Ministry of Science and Innovation under the project ENE2005-08820/ALT as part of the National Plan of Research and Development (2004-2007).

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