A dynamic model of adjustable speed hydro plants

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Abstract. The advantages of adjustable speed hydroelectric generation have been highlighted by several authors. The optimum speed for actual working conditions must be continuously implemented by means of an appropriate control system. This process gives rise to dynamic changes in operation variables. In this paper a dynamic model of an adjustable speed hydro plant is presented. The dynamic response to changes in fore bay elevation or gate position are simulated and analysed. The control system should adjust the speed progressively avoiding frequent changes to reduce unnecessary oscillations.

Key words: Adjustable speed hydro plants, dynamic response of hydro plants, regenerative frequency converters, induction generator, hydro plant control.

1. Introduction

Usually, hydroturbines are optimised for an operating point defined by speed, head and discharge [1]. At fixed-speed operation only limited deviations of head and discharge are allowed.

The application of variable speed generation schemes to hydroelectric power plants offers a series of advantages, based essentially on the greater flexibility of the turbine operation in situations where the flow or the head deviate substantially from their nominal values [2-4].

In small hydro plants, induction generators with short-circuited rotor, such as squirrel cage ones, are frequently used because they are cheaper and more robust. To allow variable-speed operation, the stator should be connected to the fixed-frequency grid through a regenerative converter. Obviously, in these cases the converter must be sized for the total generator power.

The system considered in this paper consists of a small hydro plant equipped with a variable speed induction generator connected to the fixed-frequency grid through a regenerative converter. The unit speed must be adjusted continuously to its optimum value, following changes in operational conditions.

The aim of this paper is to characterize the dynamic response of this system to variations in speed reference. A dynamic model has been developed to represent the plant dynamics including penstock, turbine, generator and converter. The response produced by specified changes in fore bay elevation and gate position is studied.

2. Hydraulic system modelling

Penstock dynamics and turbine static characteristics are included in this subsystem. Rigid water column approximation will be used. In figure 1 the Simulink® block diagram is shown.

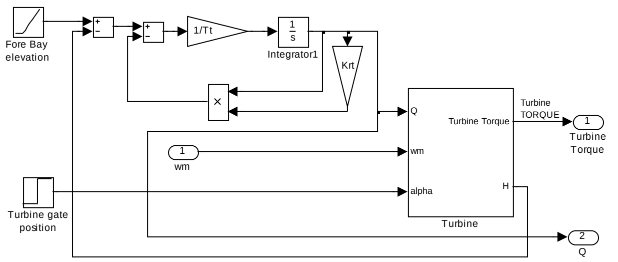

Figure 1. Hydraulic system

A Francis turbine is used in the model and its behaviour is represented by the turbine hill curves , shown in Figure 2, referred to unit speed and flow:

$$N1 = \frac{nD}{\sqrt{H}} \qquad Q1 = \frac{Q\sqrt{H}}{D^2} \qquad (1)$$

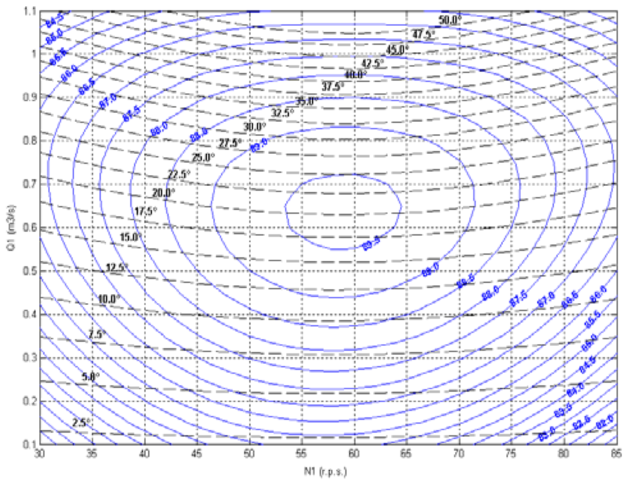

Figure 2. Turbine hill curves

3. Optimum speed module

The inputs to this module are the gate angle, *alpha* and the turbine flow, *Q*. The output is the turbine speed which gives the maximum efficiency, calculated by means of a MATLAB® function designed for interpolating into the turbine hill curves.

4. Induction generator model

The mathematical model of the induction machine is based on reference [5]. This model is described in space vector formulation in dq frame (using per unit description). The used dynamic equations are:

Electrical system equations

$$\vec{V}_s = R_s \vec{i}_s + \frac{1}{\omega_0}\frac{d\vec{\lambda}_s}{dt} + \omega_k M \vec{\lambda}_s$$
$$\vec{V}_r = R_r \vec{i}_r + \frac{1}{\omega_0}\frac{d\vec{\lambda}_r}{dt} + (\omega_k - \omega_m) M \vec{\lambda}_r \qquad (2)$$

Flux linkage-current relations:

$$\vec{\lambda}_s = L_s \vec{i}_s + L_m \vec{i}_r$$
$$\vec{\lambda}_r = L_r \vec{i}_r + L_m \vec{i}_s \qquad (3)$$

Mechanical system equations:

$$T_{elec} = \lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}$$
$$T_{turbine} - T_{elec} = J\frac{d\omega_{mec}}{dt} + B_m \omega_{mec} \qquad (4)$$

where: $\vec{V}$ is the voltage space vector, $\vec{i}$ is the current space vector, $\vec{\lambda}$ is the flux linkage space vector, M is the π/2 rotational matrix, $M = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, R is the resistance, L is the inductance, ω_0 is the base frequency, ω_k is the dq frame reference speed, ω_m is rotor speed, T_{elec} is the electromagnetic torque, $T_{turbine}$ is the torque generated by the turbine, J is the moment of inertia and B_m is the damping.

5. Complete model

The hydraulic system, the optimum speed module and the induction machine model are connected as shown in figure 3, where a PI speed controller has been included. The output of this block provides the changes in the supply frequency needed to adapt the unit speed to its optimum value. The controller gains should be adjusted appropriately to obtain a slow response.

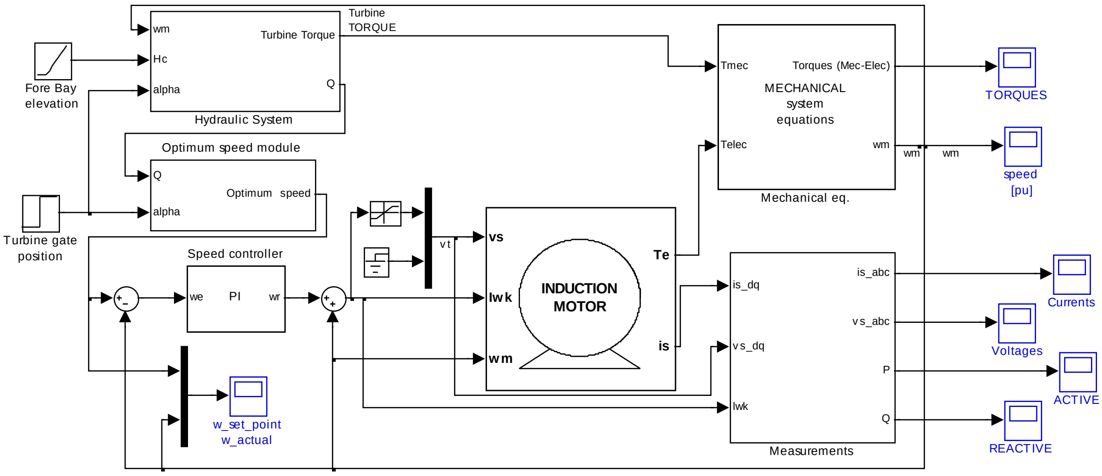

Figure 3. Dynamic model of adjustable speed hydro plant

6. Artificial Neural Network

The proposed optimum speed module (OSM) is not very computationally effective, due to the inclusion of several FOR-END loops used to obtain the optimum speed from the efficiency curves.

Besides, the produced changes in optimum speed are discrete as it is shown in figure 4.

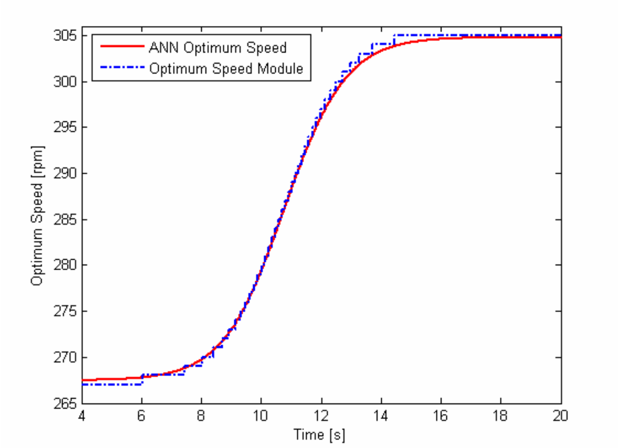

Figure 4. ANN Optimum speed vs. Optimum speed proposed by the algorithm

These little steps shown in the optimum speed elaborated by the OSM, affect to rotor speed and active power generated, as it can be observed in figure 5.

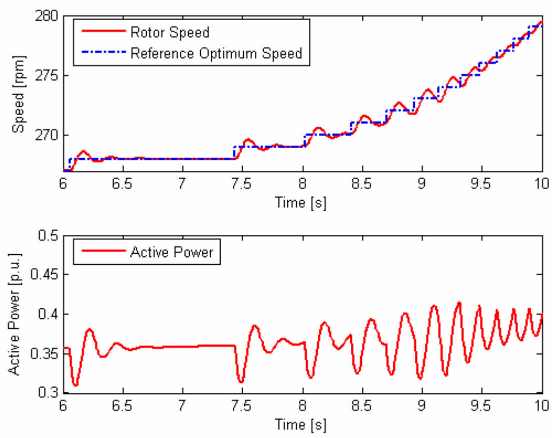

Figure 5. Rotor speed and Active Power obtained using OMS.

In order to avoid these oscillations, an Artificial Neural Network has been designed. Artificial Neural Network (ANN) is an information processing paradigm that is inspired by the way biological nervous systems. It is composed of a large number of highly interconnected processing elements, called neurons, working in unison to solve specific problems.

In this application a *multilayer perceptron* is used [6]. It has 2 neurons in the input layer (processing *Flow* and *Turbine Gate Position* information), 5 neurons in the hidden layer and 1 neuron in the output layer determining the estimated optimum speed. The ANN is trained by means of a modified back-propagation algorithm, based on Levenberg-Marquart method [6], which allows reducing the training time and improves the convergence as compared with the classical back-propagation training algorithm.

Replacing the OSM by this ANN, smoother graphs are obtained, as it is shown in figure 6.

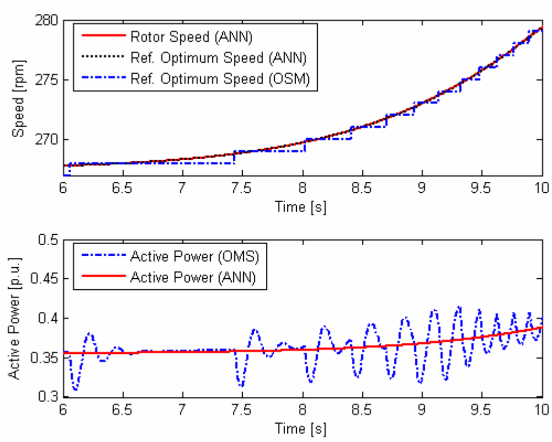

Figure 6. Reference Optimum Speed and Active Power obtained using ANN compared to Reference Optimum Speed and Active Power using OMS.

7. Simulations results

Several simulations have been done in order to evaluate the dynamic response to changes in fore bay elevation and turbine gate position.

A. Smooth changes in fore bay elevation and gate position

In the first simulation, smooth changes are applied to the fore bay elevation and turbine gate position, using a sigmoid function:

$$sigmoid(x, a, b) = \frac{1}{1 + e^{((-x+a).b)}} \qquad (5)$$

Where a and b are adjustable parameters used to change the initial position and the slope.

Initially, fore bay elevation is equal to 65 m and gate position is fixed to 15º. At 5 seconds, fore bay elevation is increased until it reaches a final value of 85 m at time equal to 20 seconds, keeping fixed the gate position. In this situation, at 25 seconds, the gate position is opened from 15º to 25º in 10 seconds. In figure 7 it is shown fore bay elevation, gate position and flow.

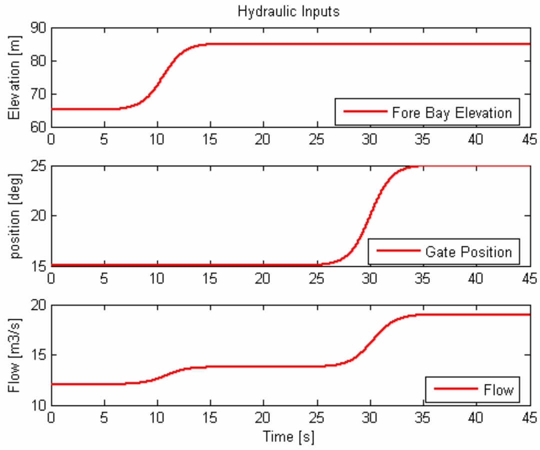

Figure 7. Fore Bay elevation, Gate Position and Flow.

Figure 8 shows the Reference Optimum Speed given by the ANN and the rotor speed. Both curves are practically indistinguishable. When the fore bay elevation increases, the optimum speed is increased too.

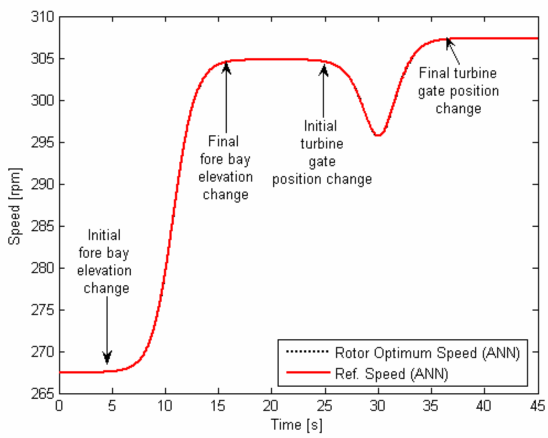

Figure 8. Reference Optimum Speed and Rotor Speed.

While the fore bay elevation is kept constant, at 25 seconds, the gate position is opened. Flow cannot change immediately, so reference speed is decreased and, when the gate position has reached its final value and flow has settled, reference speed, and rotor speed, will settle too.

Figure 9 shows the active power generated by the asynchronous machine. This magnitude changes smoothly without oscillations.

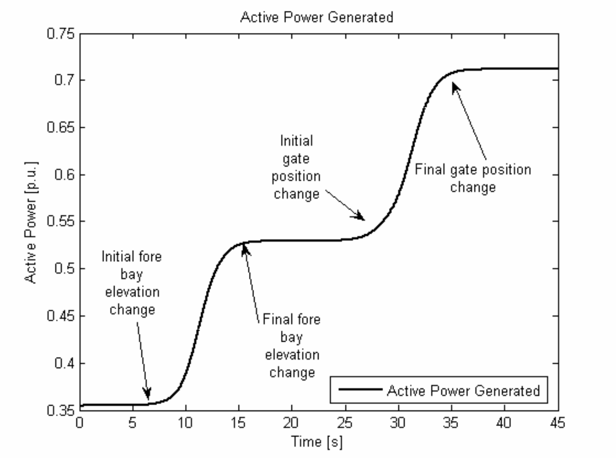

Figure 9. Active Power Generated.

B. Smooth change in fore bay elevation and abrupt change in gate position

In the second simulation, smooth change is applied to the fore bay elevation, because physically this magnitude cannot change quickly, and the turbine gate position is changed abruptly, like during an abnormal condition.

Again, fore bay elevation is equal to 65 m and gate position is fixed to 15º. At 5 seconds, fore bay elevation is increased until it reaches a final value of 85 m at time equal to 20 seconds, keeping fixed the gate position.

At 25 seconds, it takes 1 second to change the gate position from 15º to 25º, that means a maximum gate opening rate of 0.2 p.u./s. This value is in the order of magnitude of the maximum gate opening rate used in [7]. In figure 10 it is shown fore bay elevation, gate position and flow.

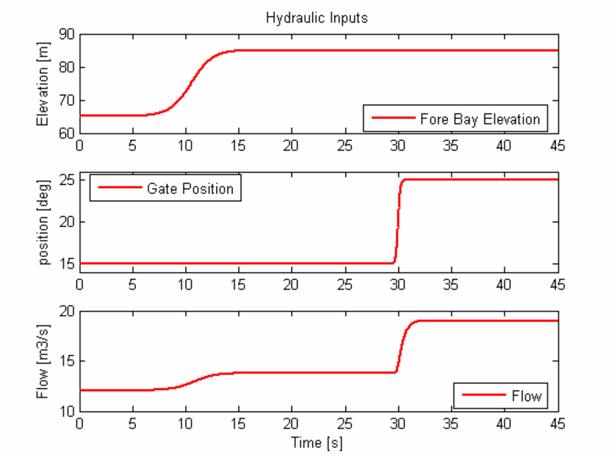

Figure 10. Fore Bay elevation, Gate Position and Flow

Figure 11 shows the Reference Optimum Speed given by the ANN and the rotor speed in this particular case. Again, both curves are practically indistinguishable.

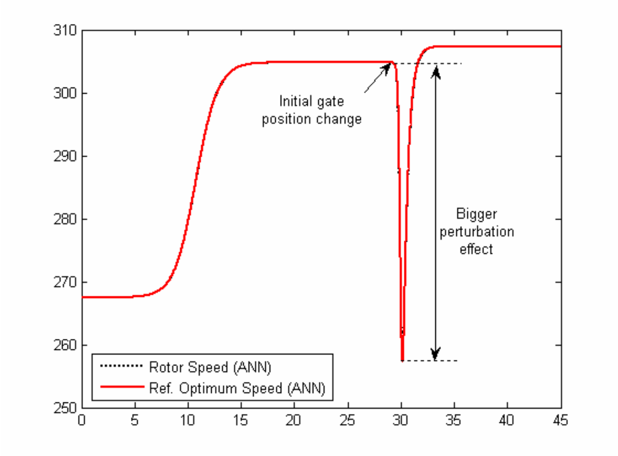

Figure 11. Reference Optimum Speed and Rotor Speed.

Comparing figure 8 and 11, it is shown that both graphs have the same settling values, but the transient effect in figure 11 is bigger, when the gate turbine position is changed quickly. This overshoot influences notably in the active power, as it can be observed in figure 12.

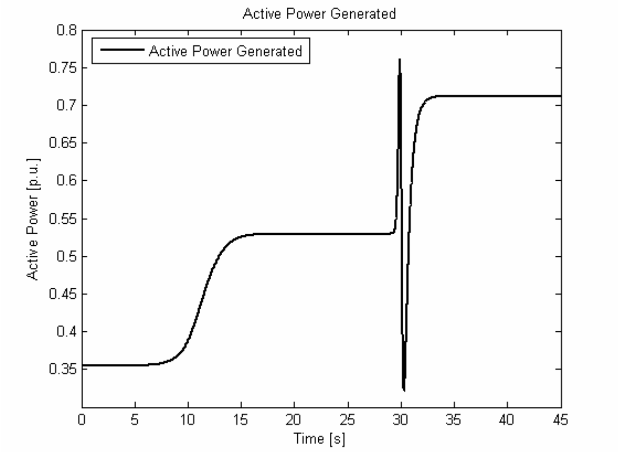

Figure 12. Active Power Generated

Active power output of the asynchronous machine is the result of multiplying its torque by its rotational speed, so the perturbation observed in Active Power (see figure 12) will be also observed in Electromagnetic Torque. Figure 13 shows the Turbine Torque and Electromagnetic Torque from time equal to 20 seconds to 40 seconds.

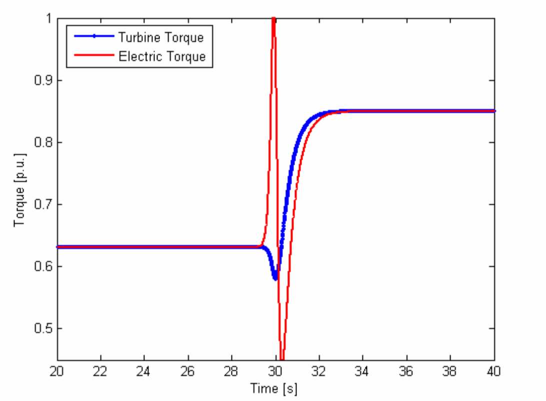

Figure 13. Torques.

8. Conclusions

A dynamic model of a variable-speed hydro plant has been built. The model includes the more relevant dynamics aspects characterizing the response to changes in supply frequency. This allows verifying the adequacy of the controller used to adapt the unit speed to its optimum value.

An original and novel optimum speed module (OMS) has been developed. This module generates an optimum speed value from the gate position and the turbine flow.

The used algorithm generates a stepped reference optimum speed that introduces some oscillatory behaviour on the rotor speed, active power and torque. In order to smooth the response, an interpolating artificial neural network has been designed and used during the rest of the simulations.

Several simulations have been run to evaluate the dynamic response to changes in fore bay elevation and turbine gate position. If these changes are smooth, generated active power and torques are smooth too.

If the turbine gate position opening (or closing) rate is large, a big overshoot in rotor speed, due to the delay in the response of the turbine flow, *Q*, is transferred to the generated active power and torque, being able to damage the mechanical system. In order to avoid this effect, it is proposed to keep constant the reference speed during these kinds of manoeuvres.

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