

## Chapter 7

# *Conclusions and Contributions*

The objective of this dissertation was to develop efficient controllers of the hydroelectric speed problem taking into account the detailed and extensive modelling necessary to represent a real world power plant. This objective was achieved through the analysis and extension of existing hydroelectric models as well as through the development of new nonlinear controllers.

### **7.1 Conclusions**

A complete and comprehensive analysis of the dynamic models of hydraulic subsystem has been made yielding the following main conclusions.

#### **Models with Surge Tank Effects**

These models are deduced from (IEEE Working Group, 1992; Quiroga and Riera, 1999), where each model has different equations that represent the dynamics of the turbine. Moreover, the equations of the derived model QR51 as well as the model WG4 may be represented as a nonlinear system in the state space. Both models are used for nonlinear controller design.

On the other hand, the linearized model  $Q_{\text{lin0}}$  proves to be useful for frequency domain studies.

### **Models with no Surge Tank Effects**

These models are adequate in cases of hydroelectric plants with no surge tank effects and short distances between the reservoir and the power plant; this means  $T_{\text{WP}} < 3$ , (Ilyinykh, 1985; Streeter and Wylie, 1975). Therefore, the behaviour of the models WG3 and WG2 and the derived models QR31 and QR32, when a disturbance in the load is introduced, show slight differences. Thus, model WG2 and QR32, QR31 are good representations of reality and may be used for nonlinear controller design in the state space.

### **Identification and Validation**

The identification process of the Susqueda power plant by different models needed the adjustment of the static gain of the Susqueda power plant by considering a nonlinear function in the calculation of the mechanical power of the turbine. This nonlinear function presents a similar shape to the efficiency curve of a Francis turbine. In case of models taken from the group of models A (based on models WG5, QR52, QR51 and WG4), a second adjustment procedure tuned the oscillation time period, due to the surge tank, by means of a five per cent modification of the measured value of the surge tank diameter.

Model A1 gave the best results (quadratic error between 0.134 and 0.142); however, models A2, A3 and A4 demonstrate also to be good approximations. Models B (based on models WG3, QR32, QR31 and WG2), Model C (based on model  $Q_{\text{lin0}}$ ) and Model D (based on model  $G_{\text{lin0}}$ ) gave an unsatisfactory identification of the hydraulic power plant since they are not able to reproduce phenomena such as the pressure waves in the surge tank or the static gain of the power plant.

The simulation of Models A1, A2 and A3 is costly due to the fact that they require more complex expressions in order to calculate the hyperbolic tangent function. Furthermore, the Model A4 proves to be the easiest to simulate since the hyperbolic tangent function is represented as a derivative function. Hence, model A4 may be expressed as a nonlinear system in the state space, and may be used in nonlinear controller design.

### **Speed Controllers Evaluation**

In order to perform the evaluation of different controllers two realistic cost functions  $f_{\text{cost(A)}}$  and  $f_{\text{cost(B)}}$  have been defined. The cost function  $f_{\text{cost(A)}}$  differs from the  $f_{\text{cost(B)}}$  in the fact that  $f_{\text{cost(A)}}$  penalises large values of time. These cost functions have proved to be very useful to perform the comparative analysis of the different controllers.

### **Nonlinear Controller Designed from Nonlinear Models with no Surge Tank Effects**

Controller NL B based on the partial state feedback linearization technique and a PI or a PI-PD structure shows the best performance since  $f_{\text{cost(A)}}$  has an average value of 15 per cent lower than the value given by a Gain Scheduling PI-PD controller, and the  $f_{\text{cost(B)}}$  has an average value of 12 per cent lower than the value of the Gain Scheduling PID controller.

Moreover, controller NL B shows, in the load rejection study, that the relation between the cost function  $f_{\text{cost(A)}}$  and the disturbance in the non-sensitive-frequency load increments ( $\Delta \bar{P}_{\text{load}}$ ) is “linear” since there are no surge tank effects and the controller reaches the steady state speedily.

### **Nonlinear Controller Designed from Nonlinear Models with Surge Tank Effects**

Controllers NL C and NL D, based on the partial state feedback linearization technique and either PI or PI-PD structures, have been developed by considering the cost functions  $f_{\text{cost(A)}}$  and  $f_{\text{cost(B)}}$ . The Controller NL D displays the best performance since the cost function  $f_{\text{cost(A)}}$  has an average value of 12 per cent lower than the values of the Gain Scheduling PI-PD. The values of the  $f_{\text{cost(B)}}$  for this controller are also the lowest for all operating points and are between 15 to 21 per cent lower than the values of the Gain Scheduling PI-PD.

The values of the cost function  $f_{\text{cost(B)}}$  for all the controllers (Gain Scheduling PI-PD, PI-PD, PID and NL D) increase when the values of the load  $\bar{P}_{\text{load}}$  increase. On the other hand the curves of the cost function  $f_{\text{cost(A)}}$  versus non-frequency-sensitive-load  $\bar{P}_{\text{load}}$ , for the same controllers, show a parabolic shape due to the penalisation of large time values considered when the  $f_{\text{cost(A)}}$  is used.

The load rejection study shows that the relation between  $f_{\text{cost(A)}}$  and  $\Delta\bar{P}_{\text{load}}$  is “quadratic” for the controller NL D. This is caused by the effects of the surge tank and the fact that the cost function  $f_{\text{cost(A)}}$  penalises large values of time and time duration.

### **Nonlinear Controllers based on the Lyapunov Function Technique**

Controllers Lyapunov 4 and Lyapunov 51 have shown that an increase of the complexity of the hydroelectric turbine model does not improve the response of the system as the difference between values of the cost function ( $f_{\text{cost(A)}}$ ) is around one per cent.

Controllers Lyapunov 4 and Lyapunov 51, when the  $f_{\text{cost(B)}}$  is considered, present cost function values with the same order of magnitude as the NL C, PID, PI-PD and NL D controllers; however, the values of the  $f_{\text{cost(B)}}$  for Lyapunov 4 and Lyapunov 51 controllers are greater than the NL C, PID, PI-PD and NL D controllers.

An interesting result from the cost function point of view is obtained by considering  $f_{\text{cost(B)}}$  in the controller Lyapunov 2. The latter presents, for some operating points, equal values of the cost function for the controllers PID or PI-PD. The terms multiplied by ‘ $a_2$ ’ are four magnitude orders smaller than the term ‘ $a_1$ ’ and there is not improvement in the rotor speed responses of the controller Lyapunov 4.

The load rejection studies show that the relation between the  $f_{\text{cost(B)}}$  versus  $\Delta\bar{P}_{\text{load}}$  is “linear” for the controllers Lyapunov 2, 4 and 51, since the cost function  $f_{\text{cost(B)}}$  penalises the speed errors and its duration, and the actions of the controller, as well as penalising the amplitude of the manoeuvres and its duration.

## **7.2 General Contributions**

In this dissertation different results have been proposed, from the development of nonlinear and linearized models of hydraulic turbines including the identification of a hydroelectric power plant, to the design of nonlinear controllers. The contributions obtained through this dissertation are summarised as follows.

### **Models of Hydroelectric Systems**

Due to the numerous hydraulic turbine models found in the literature, an important contribution has been presented by means of the study and the classification of these hydroelectric system models. Moreover, new nonlinear or linearized models, which are deduced from the classification table, are incorporated. Another contribution is the comparative analysis: on one hand the time domain analysis of the models, and on the other hand the frequency response analysis of the models, both based on real parameters of power plants.

### **Identification and Validation of the Models**

Based on dynamic behaviours of the Susqueda power plant recorded in different working conditions, the identification of this hydraulic plant has been made. The hydraulic turbine models previously analysed and classified have been used after carrying out some modifications in order to adjust the real power plant to model behaviour.

### **Design of Nonlinear Controllers Based on Differential Geometric Techniques**

Alternative or 'mixed' nonlinear controllers from nonlinear models with or without surge tank effects have been designed by combining the partial state feedback linearization technique and either PID or PI-PD features.

### **Design of Nonlinear Controllers Based on the Lyapunov Function Technique**

These nonlinear controllers have formed a second group of nonlinear controllers that have been designed in this dissertation and have represented another way to design nonlinear controllers from nonlinear models with (or without) surge tank effects.

## **7.3 Future Work**

During this dissertation some nonlinear and linearized models of hydraulic turbine, as well as new nonlinear controllers have been proposed. These developments may be extended in many cases. There are several extensions or modifications which can be explored. These include:

### **Models for Complementary Applications**

Expand the modelling study including the case of multiple penstocks and turbines supplied from a common tunnel, with either non-elastic or elastic water columns in penstocks and the tunnel.

As an initial step, models already introduced by IEEE Working Group (1992), Vournas and Zaharakis (1993), De Jaeger *et al* (1994) should be taken since they consider the coupling effect of head variations at the manifold.

### **Validation**

New real registers of other hydroelectric power plants may be considered in order to validate the models for complementary applications (multiple penstocks).

### **Nonlinear Controllers**

Considering other characteristics of the power plants the design of new type of nonlinear controllers may be developed. These may include:

#### **Nonlinear Controllers for Interconnected Systems**

In an interconnected system it is required not only the control of the frequency (speed) but also that of the control the generation of power. This control is referred to as load-frequency control (L.F.C.) or automatic generation control (A.G.C.). Therefore, new nonlinear frequency controllers may be designed.

#### **Nonlinear Controllers Based on Passivity**

Lyapunov functions are generalisations of the notion of energy in a dynamic system. Passivity represents an approximation to the construction of Lyapunov functions for feedback control purposes (Slotine and Li, 1991; Ortega *et al*, 1998), and hydroelectric plants seem normally fit to passivity techniques. A new class of controllers could be proposed as well.

**Design of Nonlinear Controllers Based on the Lyapunov Function: Consideration of the Parameters  $f_{p1}$  and  $f_{p2}$** 

The penstock head loss coefficient ( $f_{p1}$  or  $f_p$ ) and the tunnel head loss coefficient ( $f_{p2}$ ) may be considered in the models WG4 and QR51. Moreover, the penstock head loss coefficient ( $f_{p1}$  or  $f_p$ ) may be taken into account in the model WG2. Both cases these can lead to design nonlinear controllers based on the Lyapunov function technique.

**Design of Nonlinear Controllers from Model A4**

The model A4 (Chapter 4) of the hydraulic turbine may be considered either for the design of nonlinear controllers based on the partial state feedback linearization or for the design of a nonlinear controller based on the Lyapunov function technique.