Chapter 2

Previous Related Work

This chapter presents a review of previous works related to topics dealt with within this dissertation: a) Models of hydroelectric systems, where nonlinear and linearized turbine equations are considered, b) Frequency (speed) controllers for hydraulic turbines.

2.1 Models of Hydroelectric Systems

There exist many configurations and types of hydroelectric models. Some of them consider the surge tank effects, others take into account either elastic or non-elastic water columns, and many configurations consider the travelling wave effects that appear after a variation in the gate opening.

According to published papers and books, the models can be classified into the following groups:

- *Nonlinear Models*
- *Linearized Models*
- *Models for Particular Applications*

2.1.1 Nonlinear Models

Some models of the turbine system, described in previous works, can be included in this group. The analytical base of nonlinear models was deduced many years ago (Oldenburger and Donelson, 1962). The main problem at that time was the lack of analytical tools to study their nonlinear equations, and the absence of control design tools for these systems as well as the low power of the computer systems to implement the nonlinear models. These ideas were used again in the nineties in the work of the IEEE Working Group (1992), and the book of Kundur (1994).

The work of Oldenburger and Donelson (1962) presents an important contribution, from the modelling point of view, to turbine speed control. The nonlinear dynamics considered is the relationship among the turbine head, the turbine flow and the gate opening, and the mechanical power. The proposed models also consider elastic water effects, although the nonlinear dynamics is linearized at an operating point.

The IEEE Working Group (1992) presents an important synthesis of the modelling of turbine dynamics and considers the nonlinear dynamics mentioned previously. Moreover, two possibilities are presented: the first one considers as elastic the water column in the penstock and non-elastic the water column in the tunnel; the second one considers both water columns as non-elastic.

The formulation of these two works is based on the application of Newton's second law and of the continuity equation. The solution to the continuity equation is an equation that relates the upstream hydraulic circuit (reservoir-tunnel-surge tank) with the downstream hydraulic circuit (surge tank-penstock-turbine). Since the authors take into account a simplification of the solution that consists in considering the downstream flow equal to the upstream flow, they obtain an equation that could be named as *modified continuity equation*.

Kundur (1994) formulates different models of the hydroelectric system, which are based on the ideas of Oldenburger and Donelson (1962), but here the dynamics related to elastic water columns are considered as nonlinear. Moreover, the continuity equation is presented in the same way as Oldenburger and Donelson (1962) did.

Quiroga and Riera (1999) consider two modifications in the hydroelectric model from (IEEE Working Group, 1992) for a turbine with a surge tank and elastic water column in the penstock and non-elastic water column in the tunnel. These two new models allow the representation of hydroelectric dynamics in the state space as state equations, which are needed for the design of nonlinear controllers. Moreover, a comparative study is proposed, where these two new models are compared to the referenced model of the IEEE Working Group (1992), and good approximations are verified.

2.1.2 Linearized Models

The classical hydroelectric model with one zero, one pole and non-minimal phase characteristics has been the most diffused of the linearized models since it relates, by means of a simple transfer function, the mechanical power deviation with the gate opening deviation.

Authors such as Wozniak (1990), Luqing *et al* (1989), Malik *et al* (1991), Ramey and Skooglund (1970), Undrill and Woodward (1967), IEEE Committee Report (1973), and Kundur (1994) consider an ideal hydraulic turbine and non-elastic water columns. All of these authors use in their papers the above mentioned classical linearized turbine model at an operating point.

Sanathanan (1987) makes an important development by proposing a method to obtain reduced order models for hydraulic turbines with long penstocks. Moreover, he demonstrates that the first order linear model is deficient for hydraulic turbines with long penstocks due to the error produced in the transfer function phase, even at low frequencies. Although the first order model shows a stable and strongly damped transient behaviour, the real system can present undesirable oscillations. Moreover, by considering a second order model, a good approximation is obtained.

The IEEE Working Group (1992) arrives to the conclusion that linearized models are useful for the tuning of the common speed controllers utilising techniques derived from linear control analysis. In this case the parameter tuning is made for the most critical situation for the controller, which is adjusted when the plant is supplying to an isolated load at maximum output. Moreover, that paper points out that in small signal stability studies of power systems it is important to consider the dynamics of the turbine and its controller on the damping of low-frequency inter-area oscillations. This effect can be modelled by linearizing the nonlinear turbine and controller models at the appropriate operating point.

2.1.3 Models for Particular Applications

There are many papers that present improvements to adjust a nonlinear model to the needs of a particular plant by considering non-elastic water columns in the hydraulic system.

The work of Hannett *et al* (1994) presents a methodology for validating different model structures of a turbine-generator group. The point of departure is the nonlinear model from (IEEE Working Group, 1992), with no surge tank effects and a non-elastic water column in the penstock. This kind of model structure is inadequate for the hydraulic plants considered (St. Lawrence 32, B. Gilboa 3 and Niagara 1) and the model must be refined. Simulations indicate that the refined models along with the correspondent identification of the parameters produce adequate results as shown in tests performed on three hydroelectric units. The first refinement consists of introducing damping for no-load conditions; the second is made after studying the curve for electrical power versus gate opening position.

De Jaeger *et al* (1994) propose a nonlinear model for the study of hydraulic dynamics and the estimated parameters. The model is similar to the nonlinear model with no surge tank effects and a non-elastic water column in the penstock from (IEEE Working Group, 1992). The main difference is the calculation of the net mechanical power, which is calculated by means of the subtraction of the friction losses from the hydraulic power. The hydraulic power is proportional to the turbine flow multiplied by the turbine head, while the friction losses are the product of friction torque, which is a function of turbine flow and the square of the rotor speed, and the rotor speed.

Xu *et al* (1995) utilise system identification and parameter estimation techniques to model a hydro-turbine generating set. The results are based on field tests of a real machine set, and are derived by means of a recursive least square estimation algorithm.

Hannet *et al* (1998) present a dynamic simulation model of a pumped storage hydro plant for stability studies as well as the evaluation of the behaviour of this plant during large disturbances in the network. The turbine model is based on a combination of the refinements introduced in the papers of Hannett *et al* (1994) and De Jaeger *et al* (1994).

2.2 Frequency (Speed) Controllers

As stated in Chapter 1, the main function of frequency control is to regulate the turbine speed, hence, the frequency and the active power. Frequency controllers can be designed from nonlinear or linearized models. In previous works many types of frequency controllers can be found and classified as follows:

Controllers Designed from Linearized Models

Controllers Designed from Nonlinear Models

2.2.1 Controllers Designed from Linearized Models

These controllers can also be classified into two groups:

Classical Controllers

Controllers with Specific Characteristics

2.2.1.1 Classical Controllers

This group integrates those controllers described in Chapter 1: a) Mechanical-Hydraulic, b) Hydraulic-Electric and Hydraulic-Electronic, c) PI, PID or PI-PD Controllers.

Authors such as Undrill and Woodward (1967), Ramey and Skooglund (1970 and Kundur (1994), studied all these classical controllers.

The work of IEEE Standards (1988) is also a relevant document since it presents a complete guide to control hydroelectric power plants with different types of controller implementations. One relevant aspect is how to interface the controller with the unit control system.

The work of IEEE Working Group (1992) proposes for the PI controller the calculation of the transient droop by means of the inverse of the proportional gain; moreover, the reset time is given by the quotient between the proportional gain and the integral gain. When the derivative term is considered, the transient gain (inverse of the transient droop) is incremented by up to sixty per cent with respect to normal PI values. This result is obtained by tuning the PID according to the formulas proposed in that paper.

Some papers made an important contribution to the *optimisation of PI* controllers.

Wozniak (1990) presents an important contribution. This author gives a graphic approximation of the tuning of PI controllers. This method is adequate for predicting the optimal proportional (P) and integral (I) gains by considering four parameters of the hydroelectric systems. These parameters are the time constants of the water column and of the rotor inertia, and the self-regulation constants of the turbine and the loading grid.

In a more recent paper, Lausberry and Wozniak (1994) take into account an important aspect of a control algorithm which is robust with respect to the plant parameter changes. In this paper a genetic algorithm is proposed and the gains of the PI controller are optimised.

Boireau (1994) suggests different solutions to ensure turbine regulation and meet the various operating conditions of hydraulic units by using a configurable PI or a PI-PD controller.

In (Scott and Wozniak, 1995), a methodology of adaptive control is applied. This allows the automatic adjustment of the gains of the controllers when the process variables change, and provides a closed loop over a wide range of operating conditions.

The paper of Schniter and Wozniak (1995) presents a development of an optimal speed control strategy of a hydroelectric plant with a Kaplan turbine, when it is subjected to decreasing load conditions.

Some authors develop a *methodology for the optimal tuning* of controllers. Vournas and Daskalakis (1993) follow a procedure in which the optimisation process maximises the stability margins of the closed loop frequency control. They conclude that tuned values are similar to the ones obtained by the classical Painter’s formulas.

Another paper that follows the same philosophy is (Li and Malik, 1997), where an optimisation parameter algorithm based on the approximation of an orthogonal test is described. This algorithm is satisfactorily integrated to a controller of a hydraulic turbine system based on a micro-controller.

Many papers propose *modified PID*. Orelind, *et al.* (1989) introduce a controller with pre-programmed and digitally controlled gains for a hydroelectric system. The optimal gain is calculated for different operating points by minimising a quadratic objective function. Subsequently, the gains are assigned depending on the gate opening and the magnitude of the speed error. The control strategy is based on the equivalent of a double derivative (DDE) with implementation of optimal gain.

Finally, the work of Riera and Cardoner (1992) proposes a prototype of a speed and power control system, where the controller has an adaptive parameter algorithm with a Gain Scheduling structure.

2.2.1.2 Controllers with Specific Characteristics

In recent years some authors have contributed to the development of new speed controllers. Different control techniques such as nonlinear control, adaptive, optimal and robust control have been proposed.

Malik and Hope (1989) consider the hydraulic plant structure and the parameters of the hydroelectric generation unit as variable and propose a controller with variable parameters. Moreover, the system stability is analysed and demonstrated.

Arnautovic and Skataric (1991) present a method for the design of a controller for a plant with a Kaplan turbine. A design procedure for static multivariable controllers is proposed. Apart from this, a methodology for choosing the controller structure and the tuning of its parameters is also proposed.

Malik and Zeng (1995) present the mathematical development of an algorithm for a robust controller. Moreover, the calculation procedures and the results of the simulation studies are performed for this controller, based on a pole shifting adaptive control technique.

In the work of Jing *et al* (1998) a control strategy for the regulation of a hydroelectric turbine is achieved by using a discontinuous controller, and utilising a three-state valve and the classic fuzzy logic.

2.2.2 Controllers Designed from Nonlinear Models

In the bibliography the works related to controllers designed from nonlinear models are reduced to few publications summarised as follows:

In (Batlle, 1998) a design of a family of controllers by using techniques based on the Lyapunov function for a nonlinear model of a hydraulic plant with no surge tank effects and non-elastic water column in the penstock is presented.

Agee, Vu and Volk (1999) present the simulation and testing of a prototype of a digital controller for a real pumped-storage power plant. This work mainly presents the tests obtained from developments of speed and load control for the governing of the following situations: off-line, on-line interconnected and on-line isolated.

2.2.3 Controller Implementation

The work of IEEE Standards (1997) presents a wide range of applications, such as design concepts, and implementation of computer-based control systems for hydroelectric plant automation. This guide assumes that the control system logic has already been defined, so its development its not covered. Some recommendations for system testing and acceptance are provided, and study cases of actual computer-based control applications are proposed as well.

2.3 Conclusions

Models of Hydroelectric Systems

The literature on hydroelectric turbine models presents some models that can be classified into two groups. The first corresponds to the group of nonlinear models and the second is the group of linearized models.

The nonlinear models are required in those cases where large signal transient stability studies of isolated hydroelectric systems are indispensable, in controller tuning studies and in long-term dynamic studies.

On the other hand, linearized models are employed in small-signal stability studies and only for the cases of non-large penstocks (T_W < 3 sec). Small-signal studies are utilised for investigating interactions between the dynamics of the hydraulic system and the network power oscillations.

Some models from the nonlinear group are validated by means of refinement. These models are included within the group of models for particular applications.

Frequency Controllers

The majority of published works of frequency controllers are designed from linearized models of hydroelectric systems, and the classical PI or PID controllers are found in this group. Moreover, there are many publications whose objective is to optimise the proportional and integral coefficients of a PI controller. Many papers propose modified PID controllers, while others papers present controllers with specific characteristics.

The PID or PI-PD controllers need to adjust their parameters for each operating point in order to guarantee an optimal behaviour. On the other hand, nonlinear controllers have the advantage that they do not need to adjust their parameters.

Only two references of controllers designed from nonlinear models have been found. One of them refers to the design of a controller by using techniques based on the Lyapunov functions.