Chapter 1

Introduction

1.1 The Motivation

Hydroelectric power plants, like real systems, have nonlinear behaviour. In order to design turbine controllers, it was normal practice in the past, when computer systems had not achieved the present development, to consider or simplify these nonlinear behaviours by linearizing at an operating point the differential equations that represent the dynamics of the hydroelectric plant.

The main motivation of this dissertation was born as a consequence and necessity of improving and optimising the dynamic responses of hydroelectric plants, by taking into account these nonlinear behaviours, leading to more realistic dynamic models of the hydraulic turbine system and to the development and design of more efficient controllers.

This dissertation considers in general the case of isolated (or islanded) system operations; it is therefore the case of a hydroelectric power plant supplying an isolated load.

1.2 The Objectives

Two objectives are covered in this dissertation: deepening the knowledge of hydroelectric models and improving the design of controllers.

1.2.1 To Deepen the Knowledge of Hydroelectric System Models

This objective consists of performing a detailed comparative analysis of different existent hydroelectric models applied to speed control and propose new ones. For this purpose real parameters taken from many hydroelectric power plants referenced in the bibliography are utilised. Moreover, the identification of a hydroelectric power plant on the Ter River is proposed by using these previously refined models.

To obtain a reliable dynamic model of hydraulic turbine systems is an important step prior to the controller design.

1.2.2 To Design Controllers from Well Proven Models

The second objective is the development and design of frequency (speed) controllers for hydroelectric power plants by using nonlinear control techniques based on differential geometry and on the Lyapunov function. For both cases the controllers are designed from nonlinear dynamic models of hydraulic turbine systems.

1.3 Research Aims

This section introduces the purpose of this dissertation by means of two topics: 1) the first considers the *Hydroelectric Generation Systems*, and the second takes into account the *Frequency (speed) Control*. Both are described below.

1.3.1 Hydroelectric Generation Systems

Power plants are capable of presenting mainly two operating situations: the first one considers *off-line performance*. During this performance the hydroelectric plant is not connected to the power system and basically generates the minimal power (no-load) in order to prepare the generator to provide the active power that the power system demands as well as to accomplish a phase match for synchronising in as soon as possible.

The second operating situation includes *on-line performance.* This one considers normal-operating situations as steady state conditions, either turbining or pumping. The on-line performance may take into account either interconnected system operations or isolated system operation.

The responses of the off-line performance are quite different to the responses of the on-line performance.

The main components of a hydroelectric system may be classified into two groups: *the hydraulic system components* that include the turbine, the associated conduits - like penstocks, tunnel and surge tank - and its control system; and secondly *the electric system components* formed by the synchronous generator and its control system. Since this dissertation is centred on the hydraulic system, a more detailed description of this system is presented.

Hydraulic turbines may be defined as prime movers that transform the kinetic energy of falling water into mechanical energy of rotation and whose primary function is to drive a electric generator. Hydroelectric plants utilise the energy of water falling through a head that may vary between a few meters and 1500 or even 2000 meters. To manage this wide range of heads, many different kinds of turbines are employed, each one of which differs in its working components, according to head-size.

An impulsive turbine is one in which the driving energy is supplied by the water only in kinetic form, and a reaction turbine is one in which the driving energy is supplied by the water partly in kinetic and partly in pressure form. Impulsive turbines for the electric generations are also known as Pelton wheels and are normally utilised when the head is 400 meters or more.

There are two categories of reaction turbines: the Francis and the propeller turbines. In this last category the Kaplan turbine, or variable-pitch blades turbine, has the highest efficiency at all loads.

Figure 1.1 shows a schematic representation of a hydroelectric power plant with a surge tank, where a powerhouse with a Francis turbine in it is depicted.

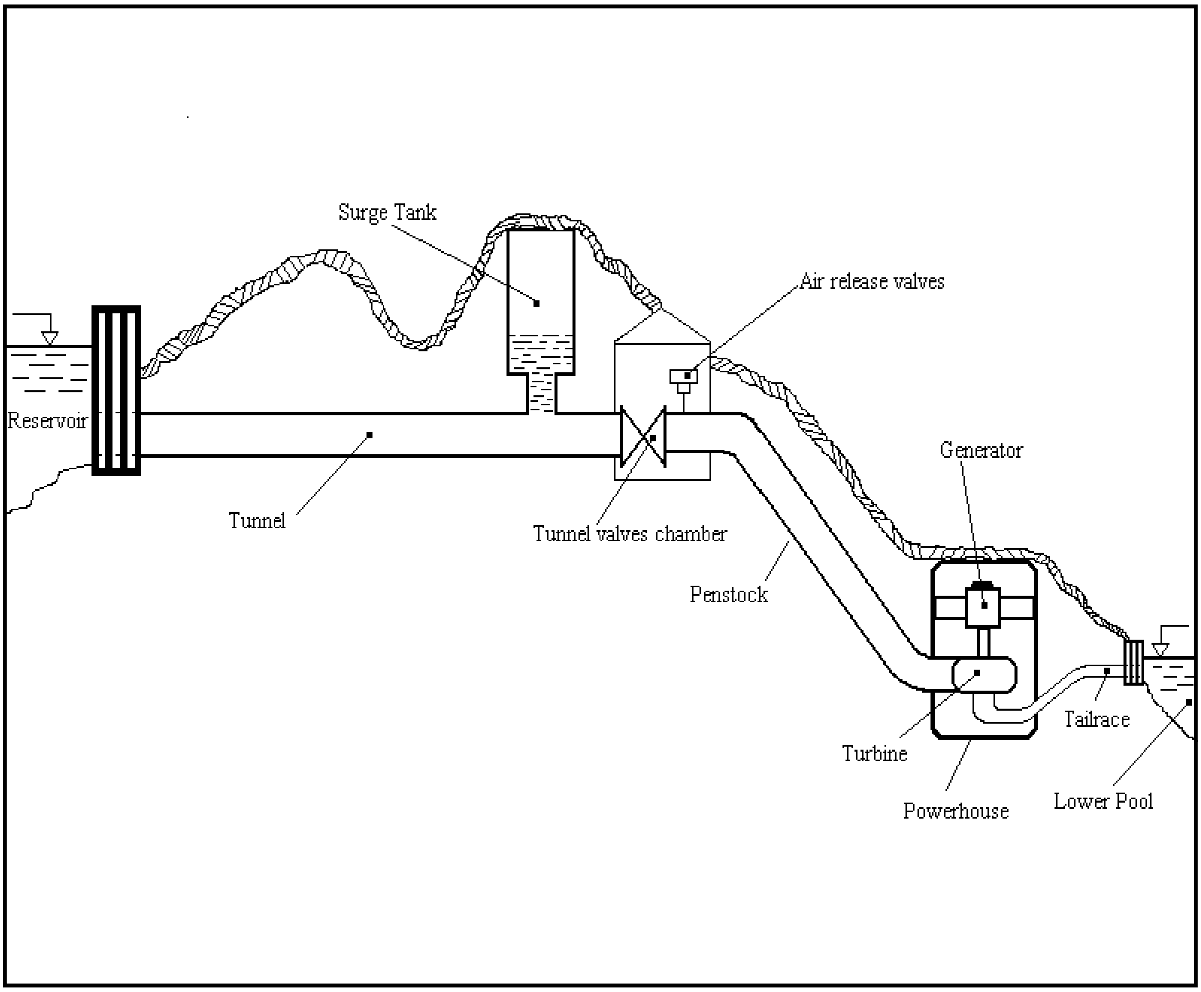

Figure 1.1: Representation of a hydroelectric power plant.

The performance of hydraulic turbines is strongly influenced by the characteristics of the water conduit that feeds the turbine. These characteristics include the effect of water inertia, water compressibility and pipe wall elasticity in the penstock. Hydroelectric turbines present a non-minimal phase characteristics due to water inertia; this means that a change in the gate opening produces an initial change in the mechanical power which is opposite to the one requested. The water compressibility effect produces travelling waves of pressure and is usually called *water hammer*. The water hammer is characterised by a sudden high-pressure rise caused by stopping the flow too rapidly. The wave propagation speed is around 1200 meters per second. In those plants where the distances between the forebay or reservoir and the turbine are quite large, a surge tank is usually utilised. The function of this tank is to hydraulically isolate the turbine from deviations in the head produced by the wave effects in the conduits. Some surge tanks include an orifice whose function is to dampen and absorb the energy of the hydraulic oscillations.

1.3.2 The Frequency Control

The prime mover governing system provides a means of controlling power and frequency; this function is commonly called load-frequency control or automatic generation control (A.G.C.). The main function of the hydroelectric power plant controller (or governor) is to regulate turbine speed, and hence voltage frequency and the active power. This function requires information of the turbine rotor speed and of the electric power in order to determine the appropriate gate opening. The main problem for controlling this plant in a convenient way arises from the fact that dynamics is nonlinear and may vary strongly with the operating point.

Normally, hydroelectric plants are subjected to two kinds of control actions: the first one is the *primary frequency control action*, where a change in the electric power consumption of the system will result in a deviation of the frequency from its steady state value, which is dependent on controller regulation characteristics and frequency sensibility with respect to load. All generating units with a primary speed control contribute to compensate the deviation by changing their total generation independently where the is load changing. The final complete restoration of the system frequency to its nominal value needs a second or *supplementary control action*, which adjusts the reference generated power load value. As the system load is varying all the time, it is necessary to vary automatically the output power of the generators.

In order to guarantee the stable satisfactory parallel operation of generating units, the controller has a droop characteristic, whose objective is to share in a proportional way the load among the generating units.

The permanent droop determines the regulation under steady state conditions and is defined as the frequency drop in percentage, or in per unit, which is needed to lead the turbine gate from the minimum to maximum opening.

The transient droop implies that for fast frequency deviations the control provides a high regulation (low gain), while for slow changes and in steady state, the control shows a normal low regulation (high gain). Apart from transient regulation, a reset time is necessary. Both of the above mentioned are needed for a stable control performance.

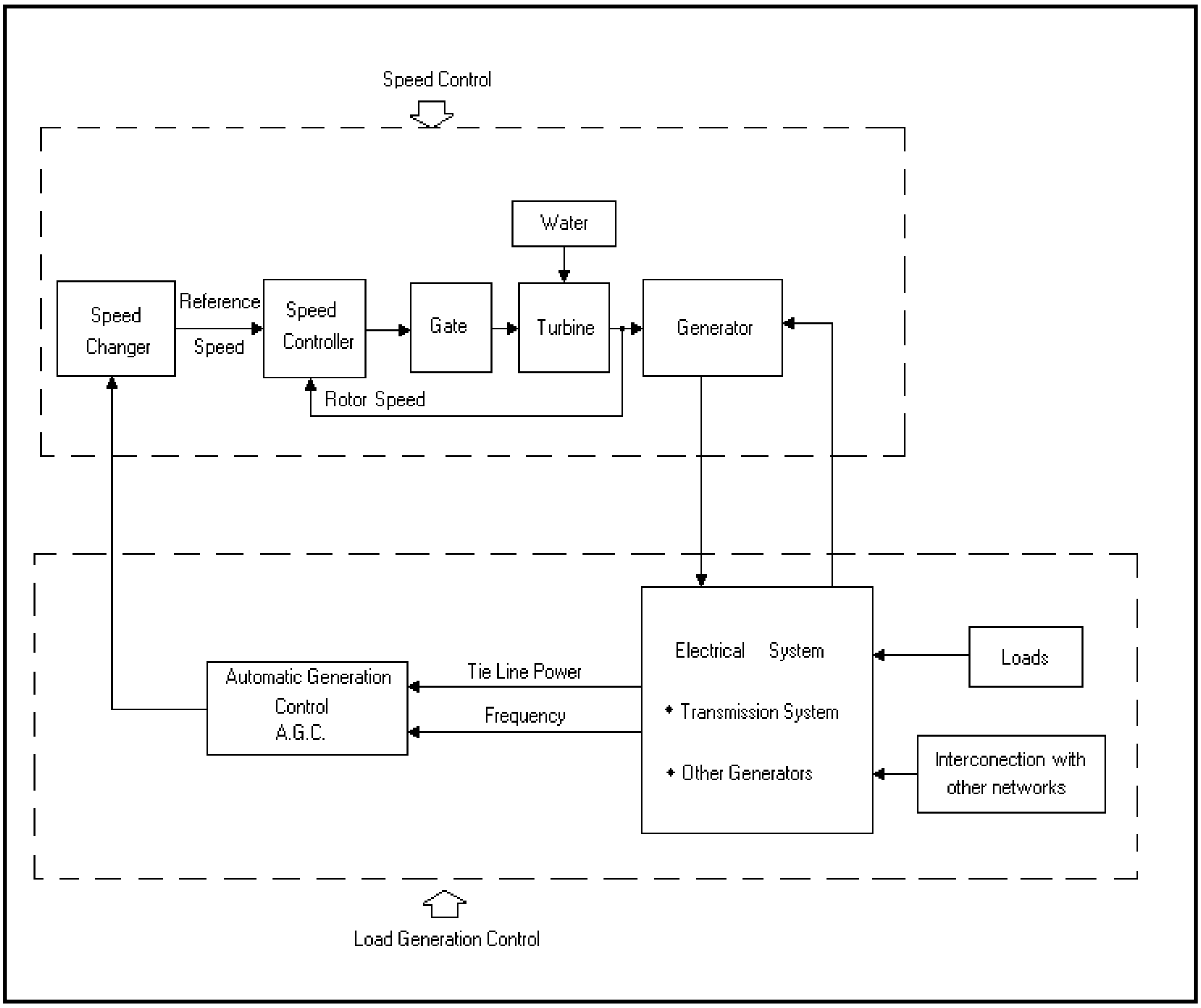

Figure 1.2: Functional block diagram that shows the relation between the hydroelectric system and the controls for a complete system.

Figure 1.2 represents, in a functional block diagram, the relationship between the hydroelectric system and its controls, the speed control and the automatic generation control. This diagram is largely utilised for interconnected system operations.

The block of the speed control in Figure 1.2 shows the basic elements of a hydroelectric system within the power system. The study of the load generation controls and electrical load dynamics are excluded from this dissertation.

Turbine controllers are usually PID-based and their implementation may include a wide diversity of configurations: from pure mechanical controllers or electric-mechanical controllers to full electronic controllers.

The controllers more often used are enumerated below:

Mechanical-Hydraulic Controllers

Mechanical and hydraulic components are utilised for the control function on older hydroelectric units. Functions like speed sensing, permanent regulation feedback and others are carried out through mechanical components. The control actions that involve higher power are performed through oleo-hydraulic components. To obtain the transient droop a dashpot is utilised, and sometimes a bypass arrangement is included to inhibit the dashpot according to the necessity of either isolated or interconnected operation.

Electric-Hydraulic and Electronic-Hydraulic Controller

Modern speed controllers for hydroelectric turbines use an electric-hydraulic or electronic-hydraulic system with similar operation to the mechanical-hydraulic controllers. The speed sensing, permanent droop, temporary droop and other functions are executed electronically.

These components give more flexibility and improve the performance since they take into account the dead bands and the time lags, although the dynamic characteristics of the electric controllers are tuned to be similar to those of the mechanical-hydraulic controllers.

PI and PID Controllers

Many electrohydraulic controllers are linear and correspond to a PID structure with three control terms: the proportional, the derivative and the integral actions, which allow high-speed responses.

The purpose of the derivative action is to extend the crossover frequency beyond the constraints imposed on the PI controllers and is beneficial for the isolated system operation, in particular for the power plants with large water starting time.

The use of a high value of the derivative gain or an increment in the transient gain produces excessive oscillations and this increases the possibility of instability when the generating unit belongs to an interconnected system. Therefore, the derivative gain is set to zero for the case of interconnected system operation and then the controller is reduced to a PI type with a transfer function equivalent to a mechanical-hydraulic controller.

Modern digital controllers have several operating modes and functions and provide operating ease and flexibility, which was not possible with old mechanical controllers. Digital controllers have proved to be very accurate and provide reliable service in an increasing number of installations, completely replacing mechanical controllers in new installations.

1.4 Organisation of the Dissertation

The remainder of this dissertation is organised as follows. Chapter 2 presents previous related work regarding the topics dealt with in this work. Chapter 3 introduces a complete study of the hydroelectric models; both nonlinear and linearized models are classified from greater to lesser complexity. A summary of the different models is given in the Appendix. Time domain analysis for nonlinear models and linearized models are presented. Frequency response analysis with stability studies are also included.

Chapter 4 describes the identification of the hydroelectric power plant of Susqueda by using the same models presented in Chapter 3, although they have to pass an adjustment process.

Chapter 5 presents the development and design of nonlinear controllers based on the technique of partial state feedback linearization. These controllers are designed from a nonlinear model either with or without surge tank effects. Moreover, this chapter describes comparative studies by using two different cost functions, and presents adjustment tables (surfaces) for representative cases.

In Chapter 6, by continuing the line proposed in Chapter 5, the development of nonlinear controllers based on the technique of the Lyapunov function is presented. The controllers are designed from nonlinear hydraulic models with surge tank effects and the following cases are considered: a) an elastic water column in the penstock and a non-elastic water column in the tunnel, and b) non-elastic water columns.

Finally, Chapter 7 summarises the complete work highlighting the main contributions and proposes future lines of research.