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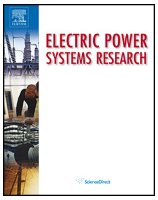

Semi-physical piecewise affine representation for governors in hydropower system generation

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ABSTRACT

This paper presents a nonlinear model for a hydraulic amplifier, a component of the governor in the speed control loop of hydroelectric power plants. The amplifier transforms the electrical signal of the controller into mechanical movement of the turbine components, including the switching characteristics. This model is used to propose, on the one hand, a Piecewise Affine (PWA) representation for the hydraulic amplifier, and, on the other hand, a methodology for estimating the model parameters using field measurements, which facilitates its practical implementation. This representation is referred to as semi-physical because the model parameters are closely related with the physical construction of the hydraulic amplifier components. Among the advantages of this PWA representation are the appropriate structuring for use in system identification methods, for estimating its parameters, and the existence of advanced control techniques that use this structure in controller design, thereby improving the load-frequency control performance. The paper concludes with a description of the results, including the parameters that were estimated by using the hydraulic amplifier model with PWA structure.

1. Introduction

The safety planning and operation of an electric power system require an appropriate representation of load-frequency control (LFC) loops in simulation environments, to guarantee required performance and to allow stability analysis of the system.

The control loop responsible for frequency control in power generation systems involves large electro-mechanical and electro-hydraulic devices, each with its intrinsic clearance and nonlinearities. If these nonlinearities, which appear in the form of dead bands, backlash, limitations on the amplitude and/or speed of the actuator, and the intrinsic uncertainties in the values of the parameters of the actuation mechanisms are not given consideration, the actual LFC performance would deteriorate in relation to the planned one, and this includes the occurrence of stability problems. These facts have been reported in the literature since the 1950s and are discussed hereafter.

The paper [1] was one of the first studies to discuss the influence of the backlash type of nonlinearity that is present in the speed control mechanism of power plants and also one of the first to describe the presence of undamped oscillations in the machine frequency arising from nonlinearities.

In the 1970s, Ramey and Skooglund [2] presented detailed models of hydraulic actuators for power system stability studies. These models were designed to reproduce speed limits on the actuating valves and amplitude limits on the gate servomotor (or gate opening). The IEEE Committee [3] also presented models for speed control systems in power plants, including the governor, and their nonlinearities. Later, Kundur and Bayne [4] explored the effect of nonlinear valves in hydraulic amplifiers for speed control and power system stability. The models included valves with speed and position limits, delays, and backlash. Moreover, models with different opening and closing times (that is, different maximum speeds) are discussed. These simulation studies led to the conclusion that an adequate representation of valves can reduce oscillations in the rotor angle.

In the late 1970s and 1980s, the sustained oscillations described in previous work were associated with the phenomenon of limit cycles generated by backlash nonlinearities of the governor representation. In this sense, Wu and Dea [5] described a parameter

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sensitivity analysis of a speed control system in an isolated area. The motivation was the sustained low frequency oscillations visualized in the frequency of the machine due to the limit cycle generated by backlash nonlinearity. Taylor and Lee [6] analyzed the backlash effects of the governor on the performance of the load-frequency controller in hydroelectric plants. Pantalone and Piegza [7] used descriptive functions to predict low-frequency limit cycles generated by backlash nonlinearities in a single area power system. Tripathy et al. [8] described the natural nonlinear dynamics of the hydraulic actuator valves and studied the effect of backlash nonlinearities in the LFC of thermal power plants. They emphasized the significant effect of these nonlinearities on the dynamic performance of the LFC system, and found that they can even cause instability. In [9], a method was described to predict and analyze sustained oscillations in the limit cycle, cause by backlash, in the speed control system of hydroelectric machines and automatic generation control.

The 2000s saw a continuation of the correlation study between nonlinearities in the governor and the performance of control systems in power plants. For example, [10] describes a study of the design of power control systems characterized by linearizing the nonlinear hydraulic amplifier model, which contains saturation, dead band, and transport delays, among other characteristics. Pico and McCalley [11] presented a detailed model of the hydraulic actuator nonlinearities and a discussion of the key strategies for speed control in hydraulic turbines and their performance in the presence of these nonlinearities. The performance degradation of the closed loop control system was illustrated through case studies that can aid the understanding of problems found in real cases. Tsay [12] analyzed an interconnected system with backlash nonlinearity models in the governor. The results showed that nonlinearities tend to produce sustained frequency oscillations, and they consequently proposed a method for selecting the controller parameters such that the oscillation level became acceptable. Recently, [13] described the design of a robust controller for coupled turbines in which the hydraulic amplifier nonlinearities (saturation and dead band type) were represented by a system with uncertain parameters for design purposes.

In this work, we are interested in analyzing the case of hydro power plants (HPPs). With suitable mathematical models to represent the LFC loop components present in HPPs, it is possible to achieve an appropriate controller design by improving the system stability either in interconnected condition or in island operation.

Therefore, the hydraulic amplifier of the governor is usually modeled by continuous dynamic systems. On the other hand, when the dynamics of these systems are governed by both logic and time, they are referred to as hybrid systems [14,15]. Systems which can be classified as hybrid are the ones known as piecewise affine (PWA) systems [16,17]. This paper proposes a new parameterization based on PWA systems customized for the components of the hydraulic amplifier of the LFC system in an HPP. This new parameterization is appropriate for the design of advanced LFC strategies such as hybrid control algorithms [18].

As far as parameter estimation methods for governor are concerned, usually nonlinearities are disregarded and the model is assumed to be a cascade of two first order models. The time constant are estimated by means of methods based on Recursive Least Squares [19], Genetic Algorithm [20], Particle Swarm Optimization [21], Bacterial Foraging Optimization Algorithm [22] and Extended Kalman Filter [23]. In the literature, non-parametric methods, such as Artificial Neural Network, have been used to estimated and model the components of the LFC [24,25].

Although previous studies have applied the results of governor nonlinear modeling to LFC, the structures that are shown are not suitable for parameter estimation using system identification methods. Moreover, even when nonlinear systems identification methods are used, the nonlinear structures, such as backlash and saturation, are generally approximated by standard continuous functions, such as NARMAX, Volterra-series, block-oriented models (Hammerstein–Wiener), and neural networks, among other models (which can be seen in more detail in [26,27]).

Another advantage of the PWA model proposed in this paper is to allow the development of system identification method for obtaining models based on field measurements. Such method is described in the present paper. In this way, it can improve the applicability of the methodology since the model will be more consistent with the field dynamics.

The paper is structured as follows. Section 2 contains a brief review of governor's modeling and a comprehensive model. In Section 3, the main concepts relating to the PWA system are presented and a semi-physical PWA representation for hydraulic amplifier components of the governor is proposed. In Section 4, an algorithm for estimating PWA model parameters is also proposed. Section 5 discusses an example consisting of a 140 MVA generator speed control loop. Finally, in Section 6, the conclusions are stated.

2. Governor and hydraulic amplifier

The block diagram shown in Fig. 1 illustrates the speed control loop in HPPs. In this figure, the speed controller, hydraulic amplifier (valves and servomotor), hydraulic prime mover (turbine/penstock), and generator dynamics are presented.

The hydraulic amplifier is responsible for transforming the electrical signal received from the controller into a mechanical power signal capable of moving the turbine components from one operation point to another, even in the presence of strong pressures caused by the hydraulic fluid in the penstock. These amplifiers are characterized by high durability and the ability to produce a powerful force with fast speed response and typically consist of three main parts: a pilot (or proportional) valve, distributor (or relay) valve, and gate servomotor, as illustrated in the block diagram in Fig. 2 [28]. The gate servomotor determines the volume of water allowed into the turbine and hence its rotation speed. The hydraulic oil flow in the gate servomotor is controlled by the pilot and distributor valves. The set pilot valve and distributor valve generate the necessary amplification from the gate position error to its servomotor.

The dynamics of the valves and systems in the hydraulic actuator are strongly nonlinear, which, consequently, makes the design of these control systems challenging. These nonlinearities have their origins in factors such as the: hydraulic fluid compressibility, complex oil flow through the valves, influence of temperature on the fluid dynamics, friction experienced by the hydraulic cylinder during movement, natural detrition by use, and physical limits imposed by the mechanical devices.

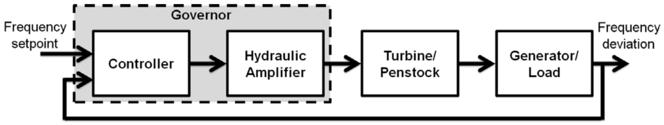

Fig. 1. Speed control system.

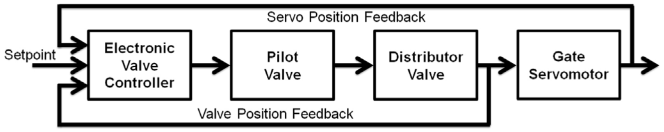

Fig. 2. Block diagram of hydraulic amplifier.