Electric Power Systems Research 133 (2016) 257–268

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A compensator design for the aged hydro electric power plant speed governors

Abdullah Altay[a], Cem Şahin[a,*], İres İskender[b], Doğan Gezer[a], Caner Çakır[a]

[a] TUBITAK MRC Energy Institute, Ankara Office, METU Campus, 06800 Ankara, Turkey
[b] Gazi University, Electric and Electronics Engineering Department, 06570 Ankara, Turkey

ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form
14 December 2015
Accepted 15 December 2015
Available online 12 January 2016

Keywords:
Hydropower generation
Electronic speed governor
Feed forward control
Backlash

ABSTRACT

This paper presents a method to design and enhance the performance of speed governors for aged Hydroelectric Power Plants (HEPP) utilizing limited number of online site tests. First, the mathematical model for the governor is generated using plant parameters. Afterwards, the aging and backlash effects are added to the model in order to match the simulation outputs with the site measurements. The feed forward and Ziegler–Nichols (ZN) methods are examined in order to mitigate the impact of backlash. Between these methods the former one is selected since it also provides island-mode stability. The updated speed governor is applied to Gezende HEPP governor and performance progress is observed.

1. Introduction

HEPPs play a crucial role in electric power industry since there is an intense interest in emission-free, sustainable energy technologies. Global hydropower generation during the year 2013 was an estimated 3750 TW h. About 40 GW of new hydropower capacity was commissioned in 2013, increasing total global capacity by around 4% to approximately 1000 GW (%16.4) [1]. The hydroelectric capacity is 23.7 GW in a total generation capacity of 69.6 GW in Turkey, occupying a share of 34.1% by January 2015 [2]. 20 GW additional generation capacity is expected until 2023. The importance of rehabilitation of existing aged HEPPs become as crucial as new HEPP constructions. 1.5 billion $ of investment is expected on the rehabilitation of existing HEPPs in Turkey until 2023 [3]. Gezende HEPP is a 22 year-old hydropower plant located on Göksu Stream which runs through the southern part of Turkey. The plant has 3×53.125 MW of generation capacity. According to the agreement between Turkish Electric Power Generation Company (EUAS) and Scientific and Technological Research Council of Turkey (TUBITAK), rehabilitation project was launched to renew the speed governor system of the plant in order to increase operational flexibility and successfully satisfy the ancillary services requirements of Turkish Independent System Operator (ISO) TEIAS.

The studies concerning the speed governors for hydroelectric power plants could be analyzed in two parts. The first group aims at modeling the water column (penstock), turbine, and speed governor itself while the second group concerns the tuning of the speed governor parameters.

Ref. [4] explains models for hydraulic turbine and speed control. Linear and nonlinear approaches are used to model hydroelectric power plants. This article is investigated for transient stability studies. Ref. [5] belongs to the first group in which the Solid Mass Approximation and elastic Water Column Equations are explained and compared. A nonlinear model for dynamic studies of hydro turbines is explained in Ref. [6]. Results of a single turbine with single Penstock model and multiple turbines with single Penstock models are compared. The parameters of nonlinear models are estimated.

The second group of studies begin with Ref. [7] in which the speed governor parameters and hydraulic coupling effects are analyzed under isolated island and black start modes. The design, construction, and experimental results of a digital speed governor are described in Ref. [8]. The digital speed governor is compared with a conventional analog speed governor. Ref. [9] discusses frequency response tests that have been performed on the hydro turbines at Apalachia HEPP. The Apalachia HEPP is composed of a long tunnel, differential surge tank, two penstocks, two Francis turbines, draft tubes. In this study, basic hydraulic equations are created and system response (frequency response) is investi-

* Corresponding author. Tel.: +0090 5337493205.
E-mail addresses: abdullah.altay@tubitak.gov.tr (A. Altay), cem.sahin@tubitak.gov.tr (C. Şahin), iresis@gazi.edu.tr (İ. İskender), dogan.gezer@tubitak.gov.tr (D. Gezer), caner.cakir@tubitak.gov.tr (C. Çakır).

http://dx.doi.org/10.1016/j.epsr.2015.12.016
0378-7796/

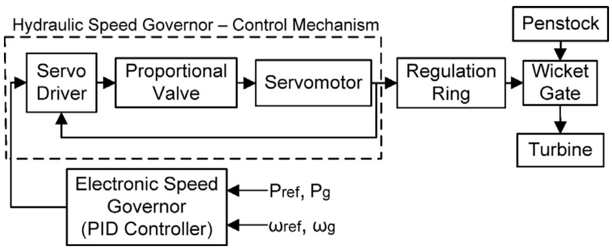

Fig. 1. Functional block diagram of speed governor system.

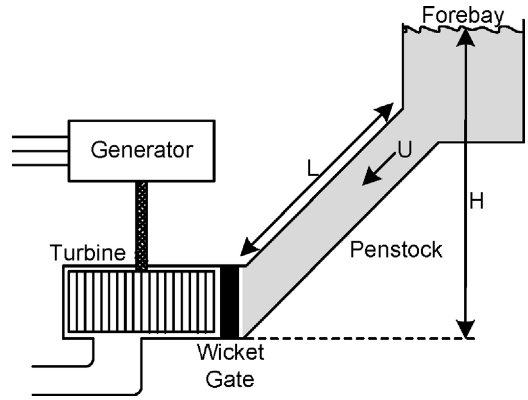

Fig. 2. Simplified schematic of a hydroelectric power plant.

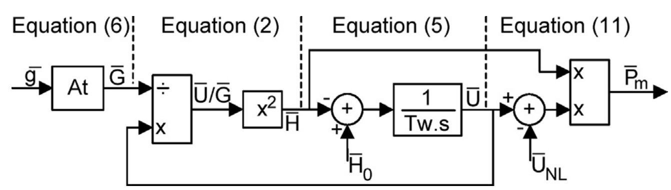

Fig. 3. Model 2, Simplified nonlinear turbine-penstock model assuming inelastic water column.

gated for different cases. In Ref. [10], parameters of PI controller are explained to tune for speed control of hydro generators. In Ref. [11], small signal state-space models for analyzing and tuning speed governor systems of hydro-turbine are explained. In Ref. [12], multiple-input and single-output control system is designed. Utilizing the pressure signal is explained for speed control of speed governor. Determination of parameters (K_P, K_I, K_D) to give an optimal response to a change in load level is provided in this article.

The upper mentioned studies consider the ideal cases in which the aging and backlashes in the mechanical systems associated with the wicket gate opening are not considered. However, actual system response and behavior is very different from ideal model simulation results when site tests are investigated in an aged HEPP. The noticed situations are delays during active power response and nonlinear behavior of wicket gate. Consequently, theoretical approach is not simply sufficient to model the characteristics of the old power plants for which the partial rehabilitation activities are widely applied in Turkey. The contributions of this paper are listed in the following items:

(1) A method to identify the backlashes in the turbine control mechanism with limited online test requirements is introduced.
(2) A compensator design is introduced in order to mitigate the backlash effect; feed-forward control method is adapted to mitigate mechanical backlashes in the wicket gate opening.
(3) The overall speed governor development process is explicitly described in a step-by-step manner and the method is demonstrated by using the data from Gezende HEPP-Mersin-Turkey. This study might help the engineers working in the field; the proposed methodology and the test results might be used for development, comparison and verification purposes.

The utilized mathematical model, parameter calculation and identification are described in Section 2. Section 3 explains proposed methodology. Section 4 gives the application of the proposed methodology in Gezende HEPP. Section 5 gives the results of the proposed method in Gezende HEPP. Section 6 presents speed governor in Gezende HEPP. Section 7 concludes the paper.

2. Mathematical model

In this section, mathematical model of turbine control system is presented. The functional block diagram of the speed governor system is given in Fig. 1.

2.1. Turbine-penstock model

Hydroelectric power generating system exhibits a high-order and nonlinear behavior. Appropriate mathematical models are essential tools for simulation of such systems. The hydraulic system and turbine-penstock models have been analyzed in literature. The models are comprised of single penstock and turbine without surge tank. The hydro turbine model is designed from penstock and turbine characteristic differential equations [4,6,13–20]. The basic equations relating to the flow of the water in penstock, turbine mechanical power and acceleration of the water defines the characteristics of turbine and penstock.

Fig. 2 illustrates the main components of a typical hydroelectric generating unit.

2.1.1. Model 1: Linear turbine-penstock model

Since linear models are obtained around an operating point, they can also be called small-signal models. The transfer function of linear models relates the turbine mechanical output power to the gate signal. The simplest model of the hydraulic turbine-penstock component is the classical transfer function for an ideal lossless turbine-penstock system which is given by [13,14,16,17].

$$\frac{\Delta \bar{P}_m}{\Delta \bar{G}} = \frac{1 - T_W s}{1 + 0.5\, T_W s} \tag{1}$$

where P_m is the mechanical power output, G is the ideal wicket gate position, T_m is the water time constant or water starting time.

2.1.2. Model 2: Simplified nonlinear turbine-penstock model assuming inelastic water column

Nonlinear turbine models are required when speed and power changes are large during islanding, load rejection and system restoration conditions. Hydrodynamics and mechanic electric dynamics are involved in nonlinear systems. Modeling of the water column is important in a system with long penstock [4,16,17]. The derivation of the following equations can be found in [13]. The following equations give the transfer function depicted in Fig. 3.

2.1.2.1. Modeling of single penstock. Eq. (2) gives the normalized water velocity in pu. Eqs. (3)–(5) are application of Newton's second law to water column in penstock.

$$\bar{U} = \bar{G}\bar{H}^{1/2} \tag{2}$$

$$\frac{\mathrm{d}U}{\mathrm{d}t} = -\frac{a_g}{L}(H - H_0) \tag{3}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{U}{U_r}\right) = -\frac{H_r}{U_r}\frac{a_g}{L}\left(\frac{H}{H_r} - \frac{H_0}{H_r}\right) \tag{4}$$