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Parameter identification of a nonlinear model of hydraulic turbine governing system with an elastic water hammer based on a modified gravitational search algorithm

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ABSTRACT

The hydraulic turbine governing system (HTGS) is a crucial control system of hydroelectric generating units (HGUs). Parameter identification of HTGS is an important issue for the modeling and control of HGUs. The parameter identification problem of HTGS is more difficult if the elastic water hammer model is considered in the system, and existing algorithms are not effective to solve it. To solve this new problem, a modified gravitational search algorithm (MGSA) has been proposed in which modifications have been made to improve the performance of the GSA from two aspects. First, the constant attenuation factor is replaced by a hyperbolic function to generate a better gravitational constant to balance the global exploration and local exploitation during different searching stages. Second, agent mutation is introduced to increase the diversity of agents and to strengthen the ability to jump out of the local minima of the GSA. The performance of the MGSA has been verified by 13 typical benchmark problems, and the experimental results and statistical analysis demonstrate that the proposed MGSA significantly outperforms the standard GSA and some other popular optimization algorithms. The MGSA is then employed in the parameter identification of a nonlinear model of HTGS with an elastic water hammer, and the experimental results indicate that MGSA locates more precise parameter values than the compared methods.

1. Introduction

Parameter identification is an important modeling technique for unknown systems that have defined model structures and unknown parameters based on the input and output data of the target system. The hydraulic turbine governing system (HTGS) is one of the most important systems of hydroelectric generating units (HGUs), and it regulates the frequency and load of the HGU. Because there are several nonlinear factors in the HTGS and because the parameters of the nonlinear model of HTGS are very difficult to measure, parameter identification is an important method to obtain unknown parameters and to build an accurate model of the HTGS.

The HTGS is a complicated nonlinear system that consists of a governor, a penstock, a hydraulic turbine, and a generator (Working Group on Prime Mover, 2002; Shen, 1998). In the literature, models of the HTGS are divided into two categories, namely, linear models (Working Group on Prime Mover, 2002; Shen, 1998; De Jaeger et al., 1994; Kishor et al., 2006; Fang et al., 2011; Chen et al., 2014; Jiang et al., 2006; Fang et al., 2009; Eker, 2004) and nonlinear models (Li and Zhou, 2011; Li et al., 2013). If two assumptions are satisfied, a nonlinear HTGS can be simplified as a linear model by neglecting nonlinear features. The first assumption is that the penstock is straight and short, and the second assumption is that the system is working under small fluctuations. Research on parameter identification of the HTGS is categorized into two groups by model type, namely, parameter identification of nonlinear models and parameter identification of linear models. Most existing research on parameter identification of the HTGS is based on simplified linear models. This type of work is relatively easy because simplified models are much simpler. Parameter identification methods for linear models include analytic methods (Trudnowski and Agee, 1995; Liu and Liang, 2007; Wang et al., 2002) and stochastic optimization algorithms (Chen et al., 2014). Because the HTGS is actually a complicated nonlinear system, analytic parameter identification methods designed for simplified linear models are not suitable for the parameter identification of nonlinear models. Therefore, parameter identification

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of nonlinear models is usually implemented by adopting stochastic optimization algorithms.

The problem of parameter identification of an unknown system can be described as a problem of optimization. By defining an objective function that estimates the error related to system parameters, the best possible set of parameters can be obtained by means of minimizing the objective function (Li and Zhou, 2011). Some popular heuristic optimization algorithms have been studied for application to problems of parameter identification of nonlinear systems and have been proved to be effective, including genetic algorithms (Aliprantis et al., 2006; Leite et al., 2004) and particle swarm optimization (PSO) (Liu et al., 2011; Kou et al., 2011). The gravitational search algorithm (GSA) is a heuristic optimization method based on the Newtonian gravity law (Rashedi et al., 2009) and has been proved to be an excellent optimization method for different types of applications, including fuzzy model identification (Li et al., 2012), classification (Han et al., 2014; Zhang et al., 2013; Li et al., 2015), wind-turbine control (Chatterjee et al., 2014), economic emission load dispatch (Jiang et al., 2014), and power systems (Mohamed et al., 2015; Ganesan et al., 2013). The GSA has demonstrated potential in parameter identification for linear and nonlinear models (Chen et al., 2014; Li and Zhou, 2011; Li et al., 2012, 2015).

In (Li and Zhou, 2011), an improved gravitational search algorithm (IGSA), which combines the searching strategy of PSO and GSA, was proposed and applied in the parameter identification of the HTGS. In (Chen et al., 2014), the IGSA proposed in (Li and Zhou, 2011) was modified by introducing chaotic mutation and was applied in the parameter identification of the HTGS. The research in (Chen et al., 2014; Li and Zhou, 2011) confirmed that GSA-based algorithms are suitable to solve the problem of parameter identification of the HTGS. However, some characteristics of the HTGS were not considered in (Chen et al., 2014; Li and Zhou, 2011): the nonlinearity of hydraulic turbines was neglected in (Chen et al., 2014), and elastic water hammer and median servomotor were simplified or neglected in both papers.

In this paper, a nonlinear model that fully considered the nonlinearity and complicated features of HTGS is studied, and a parameter identification method for this model is designed and implemented. To perform this difficult task, the GSA is introduced and modified to improve its search ability. Previous research has shown that the gravitational constant is a key factor that controls the exploration and exploitation of the GSA, and an exponent function is used as the gravitational constant function. By designing a proper variation law of the gravitational constant, the performance of the GSA would be improved significantly. A piecewise function is designed to adjust the variation of the gravitational constant of the GSA, and the improvement has been proved to be effective (Li et al., 2015). Mutation has been considered an important way to increase the diversity of agents and to avoid premature results. Differential evolution (DE) is an effective global optimization algorithm (Storn and Price, 1995; Lu et al., 2011) that is based on mutation, crossover and selection operators. The mutation strategy of DE provides an attractive choice to improve the GSA. A modified gravitational search algorithm (MGSA) based on a novel gravitational constant function and mutation strategy inspired by DE is proposed to handle the problem of parameter identification of the nonlinear HTGS with an elastic water hammer.

The rest of this paper is organized as follows. Section 2 provides a definition of the nonlinear model of the HTGS. The original GSA is introduced and the MGSA is proposed in Section 3. In Section 4, we describe the parameter identification strategy and provide experimental results to demonstrate the effectiveness of the proposed method. The conclusions are presented in Section 5.

2. Model of the hydraulic turbine governing system with an elastic water hammer

The HTGS is a complicated nonlinear system that contains four parts, namely, a hydraulic turbine governor, a penstock system, a hydraulic turbine, and a generator. The HTGS is a feedback control system that adjusts the rotation speed of the turbine. Because the generator is synchronous with the hydraulic turbine, the speed of the turbine is always obtained by measuring the angular speed of the generator. The hydraulic turbine governor calculates and amplifies the control quantity to drive the wicket gate and to control the flow of the hydraulic turbine, and the penstock is used to deliver water to the hydraulic turbine. The generator is driven by the hydraulic turbine and rotates synchronously with the turbine. A functional diagram of the HTGS is shown in Fig. 1. The complexity of the HTGS is mainly reflected in the penstock system and the hydraulic turbine. Although simplified linear HTGS models are widely used in control, parameter identification and other applications (Working Group on Prime Mover, 2002; Shen, 1998; De Jaeger et al., 1994; Kishor et al., 2006; Fang et al., 2011; Chen et al., 2014; Jiang et al., 2006), the simulations of these models involve either modeling in an ideal situation or oversimplification. In this paper, an elastic hammer model and a nonlinear turbine model are discussed in detail, and the models of the governor and generator are similar to those in (Chen et al., 2014; Li and Zhou, 2011).

2.1. Model of hydraulic turbine governor

A hydraulic turbine governor can be divided into two subsystems, namely, the controller and the servomotor. Both subsystems can be described by differential equations. At present, the parallel PID control law is widely used in the hydraulic turbine

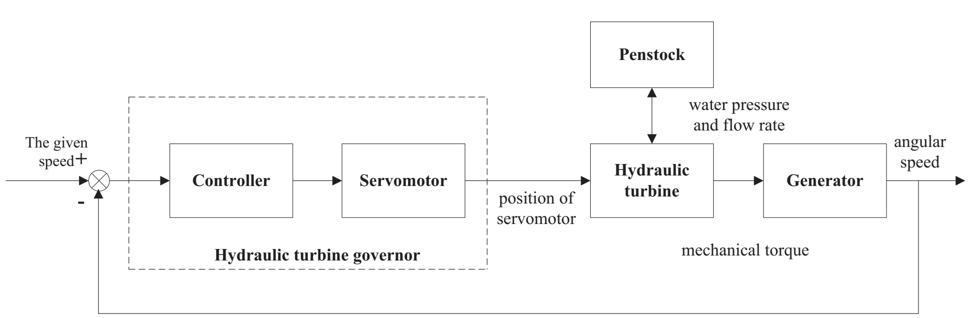

Fig. 1. Functional diagram of HTGS.