Applied Mathematical Modelling 39 (2015) 4432–4444

Contents lists available at ScienceDirect

Applied Mathematical Modelling

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

Multi-objective optimal backstepping controller design for chaos control in a rod-type plasma torch system using Bees algorithm

Reza Gholipour [a], Alireza Khosravi [a], Hamed Mojallali [b,*]

[a] Faculty of Electrical and Computer Engineering, Babol (Noushirvani) University of Technology, Babol, Iran
[b] Electrical Engineering Department, Faculty of Engineering, University of Guilan, Rasht, Iran

ARTICLE INFO

Article history:
Received 23 November 2012
Received in revised form 6 December 2014
Accepted 22 December 2014
Available online 2 January 2015

Keywords:
Backstepping controller
Bees algorithm
Control of chaos
Rod-type plasma torch system

ABSTRACT

In this study, we propose an optimal backstepping controller for chaos control in a rod-type plasma torch system. The Bees algorithm is used to determine the optimal parameters for the backstepping controller by minimizing a multi-objective function. The objective function is a weighted sum of the integral of time multiplied absolute error and the squared control signal. Our simulation results demonstrate the greater effectiveness of the proposed controller for chaos elimination in a rod-type plasma torch system compared with a sliding mode controller and a backstepping controller tuned by particle swarm optimization.

1. Introduction

Thermal plasma technology has great importance in modern industry where it is applied in the manufacture of novel materials, eliminating poisonous waste, and in facilitating more secure and effective production [1]. The efficiency of plasma technology in industrial processes is affected mainly by the characteristics of the instruments used to produce plasma, particularly plasma fluctuations. For example, in the plasma spray process, variations in the jet and instabilities in the arc may cause problems such as inserted powder particles as well as inappropriate heating, thereby degrading the quality of the coating. Other challenges hinder the progress of thermal plasma technology, thereby preventing its possible applications in industry, such as electrode erosion, low thermal competence, and the unreliable function of plasma machines, which are directly or indirectly caused by the absence of control over fluctuations. Thus, it is essential to acquire greater knowledge of the processes and applications of plasma technology, from both academic and industrial perspectives [2,3].

In recent years, a diagrammatic plasma torch has been proposed for studying fluctuations in practical tests. Based on earlier studies, fluctuations were considered to be erratic and random phenomena. However, later examinations and analysis by Ghorui et al. demonstrated that the inherent variations in plasma instruments exhibit chaotic dynamical behavior [1]. Chaos and chaotic systems have been the subjects of extensive research in recent decades [4,5]. Because chaos cannot be predicted easily and accurately, and it may lead to instability and reduce the performance of numerous applications, the aim is to control chaos as far as possible. Many methods and techniques have been proposed for the control of chaos, including the

* Corresponding author at: Electrical Engineering Department, Faculty of Engineering, University of Guilan, P.O. Box: 3756, Rasht, Iran. Tel.: +98 13 33690276 8; fax: +98 13 33690271.

E-mail addresses: rezagholipour08@gmail.com (R. Gholipour), akhosravi@nit.ac.ir (A. Khosravi), mojallali@guilan.ac.ir (H. Mojallali).

http://dx.doi.org/10.1016/j.apm.2014.12.049
0307-904X/

OGY method [6], bang–bang control [7], optimal control [8], intelligent control based on neural networks [9], feedback linearization [10], a differential geometric method [11], adaptive control [12–15], the H^{∞} control method [16], and many others [17,18].

The backstepping approach is one of the most popular techniques used in nonlinear controller design. It is capable of generating globally asymptotically stabilizing control laws to suppress and synchronize chaotic systems [19–22]. In [23,24], control using two well-known chaotic systems, i.e., Lur'e Like and Genesio-Tesi, was studied based on combining the backstepping method with chaotic particle swarm optimization (CHPSO). CHPSO comprises position and velocity updating equations and a logistic map. As a result, its application is highly complex and time consuming. In the present study, to overcome these disadvantages, we use the Bees algorithm to design an optimal backstepping controller for chaos control in a rod-type plasma torch system. The Bees algorithm involves no mathematical equations, which makes its implementation very simple.

The remainder of this paper is organized as follows. The chaotic behavior of a rod-type plasma torch system is explained in Section 2. Section 3 describes the classical backstepping method. The Bees Algorithm is summarized in Section 4. The proposed optimal backstepping controller is introduced in Section 5. In Section 6, simulation results are presented that validate the greater effectiveness of the proposed method compared with sliding mode control. Our conclusions are given in Section 7.

2. Chaotic behavior of a rod-type plasma torch system

The following equation is considered for a thermal arc plasma based on triple convection theory [1–3].

$$\dddot{F} + \Omega_2\ddot{F} + \Omega_1\dot{F} + \Omega_0 F = \pm F^3. \tag{1}$$

Thermo-physical parameters such as the plasma torch tool, flow speed of plasma gas, and arc current determine the parameters of Eq. (1). To consider the dynamical behavior of a plasma torch, the coefficients of (1) are taken from the research results reported by Ghorui et al. [1–3]. The rewritten form of Eq. (1) is as follows:

$$\dddot{F} + \ddot{F} + 50\dot{F} + \mu F = -F^3, \tag{2}$$

where μ represents the bifurcation parameter. The state-space model of system (2) can be described as follows.

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= x_3, \\ \dot{x}_3 &= -\mu x_1 - 50x_2 - x_3 - x_1^3. \end{aligned} \tag{3}$$

The three equilibrium points of system (3) are $(x_1, x_2, x_3) = (0,0,0),\ (\pm\sqrt{-\mu}, 0, 0)$ for $\mu \leqslant 0$. The Jacobian matrix of system (3) at the equilibrium point $(x_1^e, 0, 0)$ is as follows, where $x_1^e = 0$ or $x_1^e = \pm\sqrt{-\mu}$.

$$A = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -3(x_1^e)^2 - \mu & -50 & -1 \end{pmatrix}. \tag{4}$$

The corresponding characteristic equation is:

$$\lambda^3 + \lambda^2 + 50\lambda + \mu + 3(x_1^e)^2 = 0. \tag{5}$$

The stability analysis of system (3) based on the Routh–Hurwitz method shows that the equilibrium points $(0,0,0)$ and $(\pm\sqrt{-\mu}, 0, 0)$ are asymptotically stable for $0 < \mu < 50$ and $-25 < \mu < 0$, respectively. Hence, $(0,0,0)$ is an unstable equilibrium point for $\mu < 0$. Figs. 1–4, show that system (3) becomes chaotic with the initial conditions $(x_1, x_2, x_3) = (5, -2, 3)$ and $\mu = -130$. It is desirable to design a controller such that the states of the rod-type plasma torch system converge asymptotically to the unstable equilibrium point $(0,0,0)$ for $\mu < 0$.

3. Backstepping method

In control theory, backstepping is a technique used to derive control laws associated with an appropriate Lyapunov function, which guarantees the stability of nonlinear systems. The idea of backstepping design is to recursively select some appropriate functions of state variables as pseudo-control inputs for lower dimension subsystems of the overall system. Each backstepping stage yields a new pseudo-control design, which is expressed in terms of the pseudo-control designs obtained from previous design stages. A feedback controller is obtained when the design procedure is terminated. This feedback controller achieves the original design objective due to the final Lyapunov function and it is produced by summing the Lyapunov functions associated with each individual design stage.

The following steps are required to design a backstepping controller for an n-order system.

Consider an n-order system with strict feedback form as follows: