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Design of a composite recurrent Laguerre orthogonal polynomial neural network control system with ameliorated particle swarm optimization for a continuously variable transmission system

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ABSTRACT

Because the nonlinear and time-varying characteristics of the V-belt continuously variable transmission system driven by a permanent magnet synchronous motor (PMSM) are unknown, improving the control performance of the linear control design is time-consuming. To overcome difficulties in the design of a linear controller for the PMSM servo-driven V-belt continuously variable transmission system with lumped nonlinear load disturbances, a composite recurrent Laguerre orthogonal polynomial neural network (NN) control system with ameliorated particle swarm optimization (PSO), which has the online learning capability to respond to the nonlinear time-varying system, was developed. The composite recurrent Laguerre orthogonal polynomial NN control system can perform inspector control, recurrent Laguerre orthogonal polynomial NN control which involves an adaptation law, and recouped control which involves an estimation law. Moreover, the adaptation law of online parameters in the recurrent Laguerre orthogonal polynomial NN is based on the Lyapunov stability theorem. The use of ameliorated particle swarm optimization yielded two optimal learning rates for the parameters, which helped improve convergence. Finally, comparison of the experimental results of the present study with those of previous studies demonstrated the high control performance of the proposed control scheme.

1. Introduction

A V-belt continuously variable transmission (CVT) system (Guzzella & Schmid, 1995; Sattler, 1999; Kim & Vachtsevanos, 2000; Carbone, Mangialardi & Mantriota, 2005; Carbone, Mangialardi, Bonsen, Tursi & Veenhuizen, 2007; Tseng, Chen, Lin & Li, 2008; Tseng et al., 2009; Srivastava & Haque, 2009) typically consists of two springs, which are controlled using variable radius pulleys, and a chain with a belt. To set a stationary vehicle in motion, the primary pulley radius should be smaller than the secondary pulley radius for torque multiplication, torque transmitted to the secondary drive shaft, and speed reduction. To increase the output shaft speed, the radii of the two pulleys are inversely and synchronously varied and the belt length is maintained at a constant value. The CVT system can be operated at a specific speed by varying the radii of the pulleys for achieving the required torque multiplication, acceleration, and speed. This working profile provides motivation for research on CVT dynamics and nonlinear control algorithms.

The simple proportional-integral-derivative (PID) and proportional-integral (PI) controllers are the most common control algorithm. Simple methods for tuning PID and PI controllers were developed by Ziegler and Nichols (1942) in the seminal paper. The Ziegler–Nichols ultimate-cycle or closed-loop tuning has been widely known as a fairly accurate heuristic method to determine good settings of PID and PI controllers, for a wide range of common industrial processes. However, there are two essential drawbacks with the Ziegler–Nichols method. Too little information is used to characterize process dynamics. The design method, quarter amplitude damping, chosen by Ziegler and Nichols gives closed-loop systems with poor damping and poor robustness. These drawbacks have been known for a long time. The Ziegler–Nichols frequency response method for tuning PID and PI controllers is shown that this method has severe limitations (Astrom & Hagglund, 1995; Hagglund & Astrom, 2002, 2004). However, the Ziegler Nichols methods have remained very popular because of their simplicity. Recently, there are some advanced methods (Zhang, Shi & Mehr, 2011, 2012; Zhang, Shi & Liu, 2013) to tune the PID controllers. Zhang et al. (2011) proposed the design the remote PID controller for networked control systems (NCSs). The design of the digital PID controller is formulated as a synthesis problem of the static output feedback (SOF) control via an augmentation method. Additionally, Zhang et al. (2012) developed the design of

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robust H_∞ PID controllers for NCSs with disturbance/noise attenuation. The design problem of PID controllers is converted into a design problem of output feedback controllers. The proposed controller can be readily designed based on iterative suboptimal algorithms. Furthermore, Zhang et al. (2013) proposed the H_∞ step tracking control for networked discrete-time nonlinear systems with integral and predictive actions. They assume that the lumped network-induced delay lies within a known set, and that the occurrence probability for each element in the set is known a priori. Then, the delay information will be incorporated into the delay-dependent tracking controllers. The parameters for the tracking controller are derived by solving an optimization problem. Although these approaches work well in many practical situations, it is still difficult to choose optimal PID parameters in the PMSM servo-driven V-belt CVT system with nonlinear dynamics. In a previous study, a standard proportional-integral-derivative (PID)-based controller with measurements of the gear ratio used for CVT-based vehicle regulation was reported in Guzzella and Schmid (1995). The control scheme which showed satisfactory performance, involved gain scheduling based on a large set of points. The design of numerous fuzzy controllers for a CVT hydraulic module was reported in Kim and Vachtsevanos (2000). An innovative adaptive nonlinear controller using the backstepping control scheme for the CVT system in tracking the prescribed wheel speed was presented in Setlur, Wagner, Dawson and Samuels (2003). A feedback control using the μ-synthesis for a CVT system to guarantee stability and control performance was presented in Adachi, Ochi, and Kanai (2006). A nonlinear sliding mode control law employed to control the CVT shifting was presented in He, Li, Yu, and Song (2013). However, these techniques trade the controller performance against uncertainty, but require a priori estimates of parameter bounds. Meanwhile, these nonlinear control methods will lead to chattering phenomena and excite high-frequency unmodelled dynamics of the V-belt CVT system. Therefore, the composite recurrent Laguerre orthogonal polynomials NN control system with ameliorated PSO, which has good generalization ability and fast learning capability, is proposed to improve these problems. Furthermore, a V-belt CVT system with derived and simplified models, and driven by an alternating current (AC) motor has not been presented this research gap provided the research motivation for a current study.

AC motors can be classified into several types, such as permanent-magnet synchronous motors (PMSMs), switched reluctance (SR) motors and induction motors. To select an appropriate AC motor for a driven V-belt CVT system, high efficiency is one of the most critical factors to be considered. The PMSM provides higher efficiency, higher power density, and lower power loss for its size compared with SR and induction motors. In addition, field-oriented control is one of the principal vector control techniques for reducing torque ripple in a PMSM servo-driven system (Novotny & Lipo, 1996; Lin, 1997). Consequently, the torque ripple of the PMSM is lower than those of SR and induction motors. Furthermore, a PMSM that is controlled using field-oriented control, which can be achieved quickly by employing a four-quadrant operation, is considerably less sensitive to variations in the motor parameters (Novotny & Lipo, 1996; Lin, 1997). Therefore, the PMSM has extendedly been adopted in many applications such as robotics, electric power steering, and other mechatronics applications (Novotny & Lipo, 1996; Lin, 1997).

Artificial neural networks (ANNs) are a powerful learning tool that is used for executing complex tasks such as obtaining extremely nonlinear approximations and controlling dynamical systems (Narendra & Parthasarathy, 1990; Sastry, Santharam & Unnikrishnan, 1994; Arahal, Berenguel & Camach, 1998; Henriques, Gil, Cardoso, Carvalho & Dourado, 2010; Arinton, Caraman & Korbicz, 2012). The principal advantages of using ANNs are high learning ability based on optimization with an appropriate error function and high performance in approximating nonlinear functions. Various paradigms of neural networks (NNs) have been previously proposed for the tasks of system identification and control (Sastry et al., 1994; Arahal et al., 1998; Henriques et al., 2010; Arinton et al., 2012). One of the major drawbacks of ANNs is that they require numerous iterations and time-consuming intensive computations for their training. The use of functional-link NNs has been reported for reducing the computational complexity (Pao, 1989; Pao & Philips, 1995; Patra, Pal, Chatterji & Panda, 1999); they exhibit a performance similar to that of NNs, but the computational cost is considerably less. Functional-link NNs (Pao, 1989; Pao & Philips, 1995; Patra et al., 1999), which show less computational complexity and faster convergence, have been implemented for performing the tasks of system identification and control in many nonlinear systems. Recently, combinations of Laguerre functional expansions and NNs, which have been used for highly nonlinear approximation, identification, compensation, and control of systems, have been proposed (Aadaleesan, Miglan, Sharma & Saha, 2008; Mahmoodi, Poshtan, Jahed-Motlagh & Montazeri, 2009; Patra, Bornand & Meher, 2009; Zou & Xiao, 2009; Patra, Meher & Chakraborty, 2011). Aadaleesan et al. (2008) proposed a combination of a Laguerre filter and a wavelet network to approximate a memoryless nonlinearity. Another study reported the approximation of the linear and nonlinear sections of a Wiener structure by using a Laguerre filter and a general feedforward NN (Mahmoodi et al., 2009). The Laguerre-functional-expansion feedforward NN, which employs Laguerre orthogonal polynomials in the activation functions of hidden neurons to identify models of chaotic time series, was proposed by Zou and Xiao (2009). Patra et al. (2009) proposed a computationally efficient Laguerre NN based on Laguerre functional expansions for auto-compensating for the environmental reliance and associated nonlinearity in intelligent sensors. Patra et al. (2011) proposed an intelligent skill involving a computationally efficient Laguerre NN for compensating for natural sensor nonlinearity and environmental effects. Because a Laguerre NN is a single-layer NN, its computational complexity is considerably lower than that of a multilayer perceptron. However, although Laguerre-functional-expansion feedforward NNs without feedback loops can be used for static function approximation, they cannot adequately approximate the dynamic behavior of PMSM servo-driven V-belt CVT systems with nonlinear and time-varying characteristics.

Recurrent NNs, which have been used for modeling a nonlinear system and for dynamic control of the system (Chow & Fang, 1998; Brdys & Kulawski, 1999; Li, Ho & Chow, 2005; Lu & Tsai, 2008; Hsu, 2009), have received considerable attention because of their structural advantages. Because of their high computational complexity, these NNs can effectively identify and control complex dynamic systems. Therefore, in the current study, to reduce the computational complexity and enhance the identification ability of high-order nonlinear systems, the recurrent Laguerre orthogonal polynomial NN, which offers more advantages than the Laguerre orthogonal polynomial NN, including higher performance, higher accuracy, and dynamic robustness, was proposed for controlling a PMSM servo-driven V-belt CVT system with nonlinear and time-varying characteristics.

Kennedy and Eberhart (1995) were the first to propose the use of particle swarm optimization (PSO) for optimizing nonlinear functions. PSO is a population-based, self-adjusted search optimization skill. The motivation for developing the PSO method was the emulation of simplified social behaviors of animals, such as fish schooling and bird flocking. Similar to genetic algorithms (Goldberg, 2002), PSO is an evolutionary optimization tool in the field of swarm intelligence; in this method, each component is considered to be a swarm, and each swarm is a potential answer to