Mathematical and Computer Modelling 53 (2011) 2015–2030

Contents lists available at ScienceDirect

Mathematical and Computer Modelling

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

Speed and current regulation of a permanent magnet synchronous motor via nonlinear and adaptive backstepping control

Murat Karabacak[a,*], H. Ibrahim Eskikurt[b]

[a] *Department of Electronics Technology, Duzce University Duzce Higher Vocational School, Duzce, Turkey*

[b] *Department of Electronics and Computer Education, Sakarya University Technical Education Faculty, Sakarya, Turkey*

ARTICLE INFO

Article history:
Received 26 October 2010
Received in revised form 23 January 2011
Accepted 24 January 2011

Keywords:
Permanent magnet synchronous motor
Nonlinear control
Lyapunov methods
Uncertain nonlinear system
Parameter uncertainty
Backstepping

ABSTRACT

This paper proposes a new speed and current control scheme for a Permanent Magnet Synchronous Motor (PMSM) by means of a nonlinear and adaptive backstepping design. All the parameters in both PMSM and load dynamics are considered unknown. It is assumed that all state variables are measurable and available for feedback in the controller design. The final control and parameter estimation laws are derived by the design of the virtual control inputs and the Lyapunov function candidate. The overall control system is asymptotically stable according to stability analysis results based on Lyapunov stability theory. Simulation results clearly show that the controller guarantees tracking of a time varying reference speed owing to the fact that the speed and current tracking errors asymptotically converge to zero despite all the parameter uncertainties/perturbations and load torque disturbance variation. Numerical simulations reveal the performance and feasibility of the proposed controller.

1. Introduction

PMSM is receiving increased attention for high performance electric drive applications due to its considerable advantages such as high efficiency, high power factor, superior power density, large torque to inertia ratio and long life over other kinds of motors such as DC motors and induction motors [1]. However, the main disadvantage of PMSM is the need for a more complex controller for high performance electric drive applications owing to its highly nonlinear characteristics. Conventional fixed gain PI, PID controllers are widely used for the reasons of simplicity and applicability in most industrial drive applications [2]. On the other hand, such kinds of controllers may fail to meet the high performance requirements of industrial servo and speed tracking drive applications since it is highly vulnerable to parameter perturbations and unknown external disturbances of the plant [3–6]. The control strategies based on recent modern control theories are put forward to meet high performance application requirements of industrial drive applications. Fuzzy logic based controllers are robust to parameter variations and external disturbances as their design is independent of the controlled system [7–9]. Nevertheless, expert knowledge is necessary for real time application of these controllers. Many researchers have studied sliding mode variable structure control (SMVSC) because of its robustness against parameter perturbations and external disturbances; however, its main drawback is the chattering phenomenon, which restricts application of SMVSC [10,11]. The sliding mode control using smooth control law is proposed to reduce the chattering phenomenon [12,13]. Artificial intelligence based PI-PID tuning methods proposed in [14–16] have a good robustness to parameter variations and external disturbances since its design is independent of mathematical models of the controlled system. Nonetheless, real time implementation of these and such-like methods is very difficult due to its heavy computational effort and algorithm complexity. Active Disturbance

* Corresponding author. Tel.: +90 3805240098; fax: +90 3805240097.
E-mail addresses: muratkarabacak@duzce.edu.tr (M. Karabacak), eskikurt@sakarya.edu.tr (H.I. Eskikurt).

0895-7177/$ – see front matter
doi:10.1016/j.mcm.2011.01.039

Rejection Control (ADRC) strategy is first proposed by Han [17] and its concept is "dynamic compensating linearization" [18]. Although the design of ADRC is independent of the controlled object and thereby provides good dynamic performance under large variations of drive system parameters and load conditions [19,20], it is necessary to properly tune many parameters resulting from the extended state observer so as to obtain stable performance. A State Dependent Riccati Equation (SDRE) based controller, which is also referred to nonlinear quadratic optimal control, is studied in [21]. The method requires solving an Algebraic Riccati Equation (ARE) [22–27]. The design of this controller based on real time needs complex formulation and heavy computational effort. The Model Reference Adaptive System (MRAS) based adaptation mechanism using the MIT rule for the estimation of slowly varying parameters is developed to regulate parameter uncertainties and speed error of PMSM [28]. Lyapunov stability theory based robust design of MRAS speed control for PM linear motor is presented in [29,30]. Simulations and experimental results are obtained respectively. Despite the fact that the control method has good dynamic performance and strong disturbance rejection ability, it should be noted that the performance of MRAS is sensitive to parameter variations of the controlled system.

Backstepping control is a newly developed technique for the control of uncertain nonlinear systems, particularly those systems that do not satisfy matching conditions [31,32]. The most appealing point of it is to use the virtual control variable to make the original high order system simple; thus, the final control outputs can be derived systematically through suitable Lyapunov functions. An adaptive robust nonlinear controller straightforwardly derived using this control method is proposed for the speed control of PMSM [33,34]. The controller is robust against stator resistance, viscous friction uncertainties and unknown load torque disturbance. However, this approach uses the feedback linearization, which its utilization may cause to cancel some useful nonlinearities out [35]. Another adaptive nonlinear backstepping design method is proposed for the speed control of PMSM without utilization of the feedback linearization. An exact model and adaptive controller that is robust against viscous friction uncertainty and unknown load torque disturbance are compared to each other in the PMSM drive system for step reference speed [36]. It is seen that the adaptive controller provides higher performance results than the exact model controller. An improved backstepping control technique is developed by inserting the integral of velocity tracking error into the Lyapunov function. It is proved that the tracking error converges to zero for step reference speed under variations of the parameter and load torque disturbance [37]. An adaptive backstepping control is applied to the speed tracking control of PMSM with the adaptations of stator resistance, viscous friction and load torque disturbance. The control system gives good performance for step reference speed in spite of system parameters being different from normal values [38]. An implementation of PMSM speed control by means of adaptive backstepping despite the viscous friction factor, inertia parameter uncertainties and unknown load torque disturbance is realized and high performance experimental results are obtained for low pass filtered step reference speed. It is clearly revealed that the controller forces the speed error to converge to zero asymptotically [39]. An adaptive controller for speed tracking control of PMSM is proposed with the parameter uncertainties; stator resistance and inductance, inertia and viscous friction. The overall control scheme developed shows stable speed tracking performance for DC-biased sinusoidal reference speed trajectory [40]. In [41], presented adaptive backstepping control of PMSM is robust to all parameter uncertainties and load torque disturbance. The proposed method utilizes nonlinear adaptive state feedback and backstepping techniques together derived by a suitable parameter dependent Lyapunov function. It is demonstrated in the study that speed and current regulation of PMSM are accomplished for step reference speed. The adaptive backstepping controller is designed with the adaptations of stator resistance and load torque disturbance in [42]. It is clearly concluded from the simulation results that the proposed adaptive backstepping controller are quite efficient for the PMSM speed control, when the system is deviated by parameter uncertainties and load torque disturbance.

Among adaptive nonlinear control methods in the literature, backstepping design on the control of uncertain and highly nonlinear systems has excellent performance in terms of adaptation ability to the parameter uncertainties, transient and steady state performance, disturbance rejection capacity and suitability for real time implementation [32]. However, there are some important drawbacks, characteristic of which differs in respect to the methodology used in the design. Shortly, these can be given in the following: The complexity caused by regression matrices, the singularity caused by any estimation term appearing as a denominator of any control input, the over-parameterization resulting from the number of adaptive parameters more than uncertain plant parameters and the need for partial or complete model knowledge of the controlled system in the controller design. In order to deal with these drawbacks, a new nonlinear and adaptive backstepping speed tracking control design for PMSM is proposed in this study under all parameter uncertainties and unknown bounded load torque disturbance. Stability results, adaptation and control laws are derived using an appropriate Lyapunov function. The asymptotic stability of the resulting closed loop system is ensured in the sense of the Lyapunov stability theorem. The controller guarantees convergence of the speed and current tracking errors to zero asymptotically. Not only the complexity of the controller is reduced as regression matrices are not used in the design, but also singularity and over-parameterization are eliminated. The rest of the paper is organized as follows: The mathematical model of PMSM is introduced in the second section. In the third section, the overall control design is given in connection with Lyapunov stability theory. The Section 4 comprises the simulations results and discussion about the results. The achievements obtained with the proposed controller are interpreted in the last section.

2. Mathematical model of PMSM

The mathematical model of a typical surface mounted PMSM can be described in the *d*–*q* frame as follows [43]: