Contents lists available at ScienceDirect

ISA Transactions

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

Characteristics of recursive backstepping algorithm and active damping of oscillations in feedback linearization for electromechanical system with extended stability analysis and perturbation rejection

V. Anand [*,1], R. Narendran [2]

Department of Instrumentation Engineering, Madras Institute of Technology, Anna University, Chennai, India

ARTICLE INFO

Article history:
Received 17 April 2016
Accepted 7 June 2016
This paper was recommended for publication by Brent Young

Keywords:
Permanent Magnet Stepper Motor (PMSM)
Pole Placement Control
Feedback linearization
Oscillation Damping
Backstepping

ABSTRACT

In this paper, a technique for estimation of state variables and control of a class of electromechanical system is proposed. Initially, an attempt is made on rudimentary pole placement technique for the control of rotor position and angular velocity profiles of Permanent Magnet Stepper Motor. Later, an alternative approach is analyzed using feedback linearization method to reduce the error in tracking performances. A damping control scheme was additionally incorporated into the feedback linearization system in order to nullify the persistent oscillations present in the system. Furthermore, a robust backstepping controller with high efficacy is put forth to enhance the overall performance and to carry out disturbance rejection. The predominant advantage of this control technique is that it does not require the DQ Transformation of the motor dynamics. A Lyapunov candidate was employed to ensure global asymptotical stability criterion. Also, a nonlinear observer is presented to estimate the unknown states namely load torque and rotor angular velocity, even under load uncertainty conditions. Finally, the performances of all the aforementioned control schemes and estimation techniques are compared and analyzed extensively through simulation.

1. Introduction

Permanent Magnet Stepper Motors (PMSM) [1,13] are widely used in positioning systems for its efficient open-loop operation and very small step angle. Multi-link robot manipulators in robotics, biomedical instruments, satellite positioning and other motion control industries require smooth, high precision position and control of PMSM. The feedback linearization control and its relationship with DQ transformation of stepper motor were discussed in [9]. For this improved position tracking and control, nonlinear feedback control method was proposed in [11], where nonlinear observer was designed for speed estimation. The unknown load variations have the effect upon the motor dynamics under various excitation schemes. In order to achieve smoother performance during mid-frequency operation, microstepping excitation scheme can be employed. Passive components and mechanical damper can be used to improve the performance of stepper motor as in [3]. The PWM based current feedback control of stepper motor was described for minimizing torque and current ripples [25]. The idea of feedback linearization and Passivity theory are explained in [17–19]. In [5], [12] and [16], it had discussions about the simple field weakening methods for position control of Permanent Magnet Stepper Motor combined with backstepping control. Control of Motor currents reduces the motor model in to a second order model as in [14] and [15]. The papers [6–8] discussed extensively about various robust control schemes while ensuring the stability of the system dynamics. For angular position tracking, sliding mode controller algorithm was developed by [25], through position and velocity measurement and with these measurements robust control scheme was presented in [20,23].

In this paper, a critical evaluation and performance analysis of various nonlinear state estimation and control schemes for rotor position estimation is presented. The state estimation and control technique using backstepping control scheme is proposed, where the uncertainty associated with unknown load and mechanical disturbances is addressed with robustness, considering the bounded modeling errors for rotor position estimation and speed control of PMSM through position measurement. The paper is organized as follows: Section 2 consists of the mathematical model of PMSM. Section 3 discusses various control schemes and

* Corresponding author.
E-mail addresses: anandvnktsn@gmail.com (V. Anand), rng1995@gmail.com (R. Narendran).
[1] Postal address: No.23, Sai Divine Flats, 23rd Street, Ashok Nagar, Chennai 600083, India.
[2] Postal address: E-1, 4th floor, Vijay Gita Govindam, 72/74, Mahadevan Street, West Mambalam, Chennai 600033, India.

http://dx.doi.org/10.1016/j.isatra.2016.06.005
0019-0578/

Please cite this article as: Anand V, Narendran R. Characteristics of recursive backstepping algorithm and active damping of oscillations in feedback linearization for electromechanical.... ISA Transactions (2016), http://dx.doi.org/10.1016/j.isatra.2016.06.005

estimation techniques for rotor position tracking and angular velocity control. The simulation results and analysis are reported in Section 4 and concluding remarks are summarized in Section 5.

2. Mathematical model of PMSM

The electro-mechanical dynamics of two phase Permanent Magnet Stepper Motor model [1,2,11,24] is considered here as follows:

$$\begin{aligned}
\dot{\theta} &= \omega \\
\dot{\omega} &= 1/J(-KI_a \sin(N\theta) + KI_b \cos(N\theta) - B\omega - \tau_L) \\
\dot{I}_a &= 1/L(V_a - RI_a + K\omega \sin(N\theta)) \\
\dot{I}_b &= 1/L(V_b - RI_b - K\omega \cos(N\theta))
\end{aligned} \quad (1)$$

where $x=[\theta, \omega, I_a, I_b]^T$ is the state, I_a, I_b and V_a, V_b are the currents and voltages in the two phases A and B, ω is the rotor angular velocity, B is the viscous friction coefficient [N m s/rad], τ_L is the unknown constant load torque, θ is the rotor angular position and R is the resistance of phase winding. L is the winding inductance, J is the inertia of motor [kg m^2], K is the torque constant of motor and N_r is the number of rotor teeth. The magnetic coupling between the phases and the detent torque are ignored. The DQ transformation of phase voltage and current is given by the following set of equations [21]:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta) & \sin(N_r\theta) \\ -\sin(N_r\theta) & \cos(N_r\theta) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \end{bmatrix}$$
$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta) & \sin(N_r\theta) \\ -\sin(N_r\theta) & \cos(N_r\theta) \end{bmatrix} \begin{bmatrix} I_a \\ I_b \end{bmatrix} \quad (2)$$

where V_d (direct voltage), V_q (quadrature voltage) and I_d (direct current), I_q (quadrature current) are DQ transforms of the stator voltage and current. Applying DQ transformation to (1) yields:

$$\begin{aligned}
\dot{I}_d &= 1/L[V_d - RI_d + N_r L\omega I_q] \\
\dot{I}_q &= 1/L[V_q - RI_q + N_r L\omega I_d - K\omega] \\
\dot{\omega} &= 1/J[KI_q - B\omega - \tau_L] \\
\dot{\theta} &= \omega
\end{aligned} \quad (3)$$

3. Control schemes and estimation

3.1. Pole Placement by state feedback

In Pole Placement Control Technique, the state variables are available for measurement and feedback since an assumption is made that the system is completely state controllable, whereas the control inputs are unconstrained. The state feedback control law for the motor dynamics is of the form:

$$U = -K * X. \quad (4)$$

The resulting closed loop system is:

$$\dot{X} = (A - (B * K)) * X \quad (5)$$

where K is the gain matrix which helps in placement of the closed loop poles in desired pole locations. Here, a polynomial approach is utilized for the pole placement technique using Diophantine equations, which ensure the stability of closed loop system wherein its order is the sum of plant and controller order. The Diophantine equations involve finding all the unknown variables which are suitable for all the variables. Here the closed remainder theorems with pair wise co prime integers greater than one are used (Figs. 1 and 2).

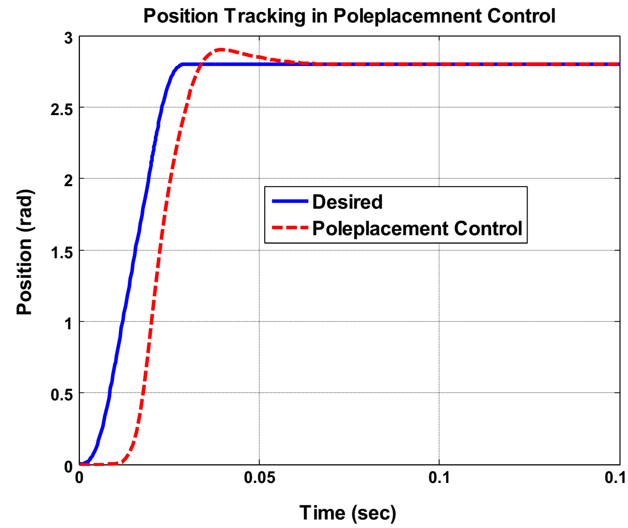

Fig. 1. Rotor position tracking in Pole Placement Controller.

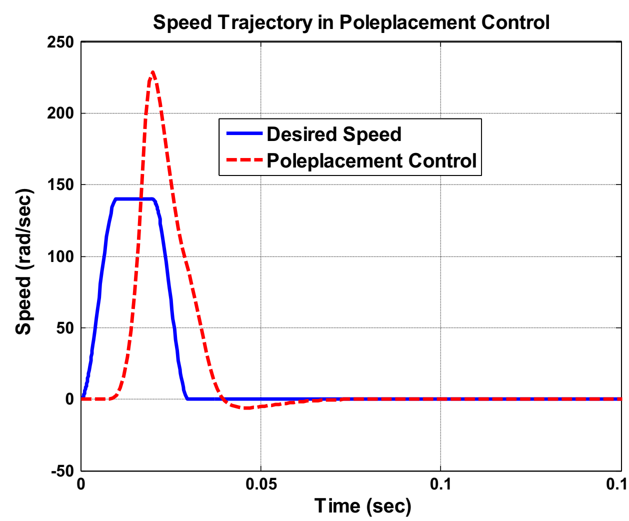

Fig. 2. Rotor speed tracking in Pole Placement Controller.

3.2. State feedback linearization control

In order to reduce the errors in the conventional controller and to ensure close tracking performances, an optimal state feedback linearization control scheme (FBL) is presented and studied (Figs. 3 and 4). It linearizes the system by changing the input voltages in the state variables. Now, applying feedback linearization technique to the DQ transformed equations:

$$\begin{aligned}
V_d &= -N_r\omega L I_q + V_{dr} + N_r\omega_r L I_{qr} + L u_d \\
V_q &= N_r\omega L I_d + V_{qr} - N_r\omega_r L I_{dr} + L u_q \\
u_d &= k_{11}(I_{dr} - I_d) \\
u_q &= k_{22}(I_{qr} - I_q) + k_{23}(\omega_r - \omega) + k_{24}(\theta_r - \theta) + k_{25}\xi
\end{aligned} \quad (6)$$

where $\xi = \int_0^t (\theta_d(t) - \theta(t))dt$ and u_d, u_q are the output comprising of gains multiplied by the errors in current, position and speed. These equations are obtained from the tracking error ε which is defined as:

$$\epsilon \triangleq \left[I_d - I_{dr},\ I_q - I_{qr},\ \omega - \omega_r,\ \theta - \theta_r \right]^T$$

The feedback term u is a function of ε i.e.,

$$u = -K\epsilon$$

Please cite this article as: Anand V, Narendran R. Characteristics of recursive backstepping algorithm and active damping of oscillations in feedback linearization for electromechanical.... ISA Transactions (2016), http://dx.doi.org/10.1016/j.isatra.2016.06.005