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Adaptive Backstepping Controller of PMLSM

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***Abstract*—In this paper, a nonlinear adaptive speed controller for permanent magnet linear synchronous motors based on a newly developed adaptive recursive Backstepping control approach for a permanent magnet synchronous motor drive is discussed and analyzed. The Backstepping technique provides a systematic method to address this type of problem. It combines the notion of Lyapunov function and a controller procedure recursively. The adaptive Backstepping control approach is utilized to obtain the robustness for mismatched parameter uncertainties. The overall stability of the system is shown using Lyapunov stability theorem. The simulation results clearly show that the proposed scheme can track the speed reference.**

***Keywords*— PMLSM; Parameter estimation; Adaptive Backstepping Control; Speed Control.**

I. INTRODUCTION

Permanent magnet linear synchronous motors (PMLSMs) have been widely used for industrial robots, machine tools, semiconductor manufacturing equipment, automatic inspection machines etc. [1] The main features of PMLSM are high force density, low losses, high dynamic performance and most importantly, high positioning precision associated with mechanical simplicity [2], [3]. However since mechanical transmission devices are eliminated, the effects of model uncertainties such as parameter variations and external perturbation in PMLSM drives are directly transmitted to the load [1]. Even worse, the load force is always unknown. All these factors make controller design for a PMLSM difficult when high speed and high precision are required in the real application.

The vector control technique (field-oriented control) is one of the most important closed loop techniques for AC machines in variable speed applications. [4] Using this control technique, the torque and flux can be decoupled so each can be controlled separately. However, for a higher performance requirement such as robots and machine tools, this method may be not sufficient during the speed transient. This led to some research in PMLSM vector control algorithm using nonlinear control theory [4], [5].

Nonlinear control algorithms thus become a natural solution for controlling the PMLSM. Recently, with the rapid progress in power electronics, microprocessors, especially digital signal processors (DSPs), and modern control theories, many researchers have aimed to develop nonlinear control methods for the PMLSM, and various algorithms have been proposed, e.g., adaptive control [6], [7], [9], robust control [8], [10], sliding-mode control [11], [12], input–output linearization control [13], and intelligent control [13], [14], [15]. These algorithms have improved the control performance of PMLSM from different aspects.

The technical proposed in our work is to control design law for the PMLSM to achieve high statics and dynamics performance. This technique is based on the Backstepping technique which establishes a controller procedure recursively to build a systematic and robust control law asymptotically stable according to the Lyapunov theory of stability [4]. The influence of the change some parameters and of the perturbation of charge can be greatly reduced by the introduction of adaptive law, in order to ensure high accuracy speed control.

II. PMLSM SYSTEM

The dynamics of PMLSM can be described as follows [17,18]:

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \frac{L_q \pi}{L_d \tau} v i_q + \frac{1}{L_d} u_d \tag{1}$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \frac{L_d \pi}{L_q \tau} v i_d - \frac{\psi \pi}{L_q \tau} v + \frac{1}{L_q} u_q \tag{2}$$

$$\frac{dv}{dt} = \frac{3\pi}{2\tau M} i_q (\psi + (L_d - L_q) i_d) - \frac{F_L}{M} - \frac{B_m}{M} v \tag{3}$$

Where i_d, i_q and v are the state variables which represent direct-axis current, quadrature-axis current and linear speed, respectively, and u_d, u_q the direct-axis and quadrature-axis primary voltage components, respectively, M is the total mass of load, B_m the viscous damping coefficient, R_s the primary winding resistance, L_d, L_q the direct-axis and quadrature-axis primary inductors, respectively, ψ the permanent magnet flux, τ the polar pitch, and F_L is the load force [19].

III. FUNDAMENTALS THEOR OF BACKSTEPPING CONTROL

The recursive backstepping control method is suitable for strict-feedback systems that are also known as “lower triangular”[20,21]. An example of strict-feedback systems is:

$$\begin{aligned} \dot{x}_1 &= f_1(x_1) + g_0(x_1) \cdot x_2 \\ \dot{x}_2 &= f_2(x_1, x_2) + g_0(x_1, x_2) \cdot x_3 \\ &\vdots \\ \dot{x}_n &= f_n(x_1, x_2 \cdots x_n) + g_0(x_1, x_2 \cdots x_n) \cdot u \end{aligned} \tag{4}$$

Where $x_n \in R$ for $n = 1,2,3$ are the system states, $u \in R$ is the control input and $f_n(x_n) : R \to R$ are known functions. The objective is to design a state feedback control law such that $x_1, x_2, x_3 \to 0$ as $t \to 0$. Similarly to the integrator backstepping case,

Step1 the idea is to use the state variable x_2 as an input for the stabilization of x_1 Consider the Lyapunov function $V_1 = \frac{1}{2} x_1^2$ .The derivative of V_1 along the trajectory of x_1 is computed as:

$$\dot{V}_1 = x_1 (f_1(x_1) + x_2) \tag{5}$$

The objective of this step is to find a control law $\phi_2(x_1)$ with $\phi_2(0) = 0$, such that when $x_2 = \phi_2(x_1)$ then $V_1(x_1) \le -W_1(x_1)$ where W_1 is a positive definite function for every $x_1 \in R$. An obvious choice would be to remove the effect of the function $f_1(x_1)$ and inject a stabilizing feedback term. Thus, we pick:

$$\phi_2(x_1) = -f_1(x_1) - k_1 x_1 \tag{6}$$

Where k_1 is a positive gain. This choice yields $\dot{V}_1 =\le -k_1 x_1^2$ .Denote the error $e_2 = x_2 - \phi_2(x_1)$

Step2 Using the new coordinate e_2 the system given in (4) can be written as:

$$\begin{aligned} \dot{x}_1 &= -k_1 x_1 + e_2 \\ \dot{e}_2 &= -\dot{\phi}_2(x_1) + f_2(x_1, e_2) + x_3 \\ \dot{x}_3 &= u \end{aligned} \tag{7}$$

The implementation of the derivative $\phi_2(x_1)$ does not require a differentiator since:

$$\dot{\phi}_2 = \frac{\partial \phi_2}{\partial x_1} [f_1(x_1) + x_2] \tag{8}$$

Let $V_2(x_1, e_2) = \frac{1}{2}(x_1 + e_2^2)$ .The goal of the second design step is to determine a pseudo control $\phi_3(x_1, e_2)$ with $\phi_3(0,0) = 0$ such that when $x_3 = \phi_3(x_1, e_2)$ then $\dot{V}_2(x_1, e_2) \le -W_2(x_1, e_2)$ where W_2 is a positive definite function for every x_1, e_2.

Consequently, the derivative of V_2 along the solutions of x_1, e_2 is :

$$\begin{aligned} \dot{V}_2 = -k_1 x_1^2 + e_2 (x_1 - \dot{\phi}_2(x_1) \\ + f_2(x_1, e_2) + \phi_3(x_1, e_2)) \end{aligned} \tag{9}$$

An obvious choice would be:

$$\phi_3(x_1, e_2) = -x_1 + \dot{\phi}_2(x_1) - f_2(x_1, e_2) - k_2 e_2 \tag{10}$$

Where k_2 is a positive constant. In this case

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$$\dot{V}_2 = -k_1 x_1^2 - k_2 x_2^2 \tag{11}$$

Step 3 Similarly to $\dot{\phi}_2$ the computation of $\dot{\phi}_3$ does not require a differentiator. Using $V_3 = V_2 + \frac{1}{2} e_3^2$ as a candidate Lyapunov function one has:

$$\dot{V}_3 = -k_1 x_1^2 - k_2 e_2^2 + e_3 (e_2 - \dot{\phi}_3 (x_1, e_2) + u) \tag{12}$$

The choice of u is:

$$u = -e_2 + \dot{\phi}_3 (x_1, e_2) - k_3 e_3) \tag{13}$$

Where k_3 is a positive constant. This choice yields:

$$\dot{V}_3 = -k_1 x_1^2 - k_2 e_2^2 - k_3 e_3^2 \tag{14}$$

IV. ADAPTIVE BACKSTEPPING CONTROLLER DESIGN

The control objective is to design a recursive adaptive control system and make the output track the reference speed. Its basic method is to decompose a complex nonlinear system into subsystems whose number is less than the system order and then design Lyapunov functions and virtual amount for every subsystem by backstepping reverse recursive designs until the whole controller designed completely [16].

It is obvious that the dynamic model of PMSM is highly nonlinear because of the coupling between the speed and the stator currents. According to the vector control principle, the direct axis current id is always forced to be zero in order to orient all the linkage flux in the d axis and achieve maximum torque per ampere.

$$e_1 = v_{ref} - v \, . \tag{15}$$

And its derivative is:

$$\dot{e}_1 = \dot{v}_{ref} - \dot{v} \, . \tag{16}$$

The Lyapunov stability function defined as:

$$V_1 = \frac{1}{2} e_1^2 \, . \tag{17}$$

And the derivative of V_1 is:

$$\dot{V}_1 = e_1 \dot{e}_1 = e_1 (\dot{v}_{ref} - A i_q + \frac{F_r}{M} + \frac{f_c}{M} v) \, . \tag{18}$$

Where, k_1 is the closed-loop feedback constant. The speed control tracking is achieved if one defines the following stabilizing functions:

$$\begin{cases} i_{qs} = \frac{1}{A} (\dot{v}_{ref} + \frac{F_r}{M} + \frac{f_c}{M} v + k_1 e_1) \\ i_{ds} = 0 \end{cases} \tag{19}$$

i_{qs}, i_{ds} are the references currents. Substituting (19) into (18) yields

$$V_1 = -k_1 e_1^2 \, . \tag{20}$$

Thus the virtual control is asymptotically stable. Since the parameters F_r , R_s and L_s are unknown we must use their estimate values ($\hat{F}_r$, $\hat{R}_s$ and $\hat{L}_s$) in (19). Thus, let us define

$$\begin{cases} i_{qref} = \frac{1}{A} (\dot{v}_{ref} + \frac{\hat{F}_r}{M} + \frac{f_c}{M} v + k_1 e_1) \\ i_{dref} = 0 \end{cases} . \tag{21}$$

Step 2 The error currents can be defined as:

$$\begin{cases} e_2 = i_{qref} - i_q \\ e_3 = i_{dref} - i_d \end{cases} \tag{22}$$

Where i_{qref}, i_{dref} are the virtual currents of precedent step.

For the recursive control and according to the equations (21), (22) and (16), the $\dot{e}_1$ can be rewritten as:

$$\dot{e}_1 = A e_2 - k_1 e_1 - \frac{\tilde{F}_r}{M} \tag{23}$$

From (22) and (3), the time derivatives of tracking error currents are rewritten as:

$$\begin{cases} \dot{e}_2 = \frac{1}{A} \begin{bmatrix} \ddot{v}_{ref} + \frac{\dot{\hat{F}}_r}{M} + \frac{f_c}{M} (A i_q - \frac{\hat{F}_r}{M} - \frac{f_c}{M} v) \\ + k_1 (A e_2 - k_1 e_1 - \frac{\tilde{F}_r}{M}) \end{bmatrix} + \\ \qquad \frac{R_s}{L} i_q + \frac{\pi}{\tau} v i_d + \frac{\psi \pi}{L \tau} v - \frac{1}{L} u_q \\ \dot{e}_3 = \frac{R_s}{L} i_d - \frac{\pi}{\tau} v i_q - \frac{1}{L} u_d \end{cases} \tag{24}$$

To analyze the stability of this system we propose the following Lyapunov function as:

$$V_2 = \frac{1}{2} e_1^2 + \frac{1}{2} \hat{L} e_2^2 + \frac{1}{2} \hat{L} e_3^2 + \frac{1}{n_1} \tilde{F}_r^{\,2} + \frac{1}{n_2} \tilde{R}_s^{\,2} + \frac{1}{n_3} \tilde{L}^2 \tag{25}$$

Where n_1, n_2 and n_3 are positive design constants of adaptive gains.

According to (23), (24) and (25), the derivative of V_2 can be rewritten as:

$$\dot{V}_2 = e_1(Ae_2 - k_1e_1 - \frac{\tilde{F}_r}{M}) + e_2\left\{\begin{array}{l}\frac{L}{A}\left[\begin{array}{l}\ddot{v}_{ref} + \frac{\dot{\hat{F}}_r}{M} + \frac{f_c}{M}(Ai_q - \frac{\hat{F}_r}{M} - \frac{f_c}{M}v)\\ + k_1(Ae_2 - k_1e_1 - \frac{\tilde{F}_r}{M})\end{array}\right]\\ + R_s i_q + L\frac{\pi}{\tau}vi_d + \frac{\psi\pi}{\tau}v - u_q\end{array}\right\} \quad (26)$$

$$+ e_3(R_s i_d - L\frac{\pi}{\tau}vi_q - u_d) + \frac{1}{n_1}\tilde{F}_r\dot{\tilde{F}}_r + \frac{1}{n_2}\tilde{R}_s\dot{\tilde{R}}_s + \frac{1}{n_3}\tilde{L}\dot{\tilde{L}}$$

If the following d-q axes control voltage are selected:

$$u_q = Ae_1 + \frac{\hat{L}}{A}\left[\begin{array}{l}\ddot{v}_{ref} + \frac{\dot{\hat{F}}_r}{M} + \frac{f_c}{M}(Ai_q - \frac{\hat{F}_r}{M} - \frac{f_c}{M}v)\\ + k_1(Ae_2 - k_1e_1 - \frac{\tilde{F}_r}{M})\end{array}\right] + \hat{R}_s i_q + \hat{L}\frac{\pi}{\tau}vi_d + \frac{\psi\pi}{\tau}v + k_2e_2 \quad (27)$$

$$u_d = \hat{R}_s i_d - \hat{L}\frac{\pi}{\tau}vi_q + k_3e_3$$

$$\dot{\tilde{F}}_r = n_1\left[\frac{e_1}{M} + e_2(\frac{\hat{L}k_1}{AM})\right]$$

$$\dot{\tilde{R}}_s = n_2\left[e_2 i_q + e_3 i_d\right]$$

$$\dot{\tilde{L}} = n_3\left[\begin{array}{l}\frac{e_2}{A}\left[\begin{array}{l}\ddot{v}_{ref} + \frac{\dot{\hat{F}}_r}{M} + \frac{f_c}{M}(Ai_q - \frac{\hat{F}_r}{M} - \frac{f_c}{M}v)\\ + k_1(Ae_2 - k_1e_1 - \frac{\tilde{F}_r}{M})\end{array}\right]\\ + e_2\frac{\pi}{\tau}vi_d - e_3\frac{\pi}{\tau}vi_q\end{array}\right] \quad (28)$$

Therefore, substituting (27) and (28) into (26), we are able to obtain:

$$\dot{V}_3 = -k_1e_1^2 - k_2e_2^2 - k_3e_3^2 \quad (29)$$

So the system is globally asymptotically stable in the presence of parametric uncertainties.

V. NUMERICAL SIMULATION AND ANALYSIS

In order to validate the theoretical analysis and to establish the effectiveness of the adaptive Backstepping control of PMLSM drive, digital simulation at different operating conditions of the system drive are presented. The simulation was performed with the MATLAB–Simulink software environments using the motor parameters listed in Table 1.

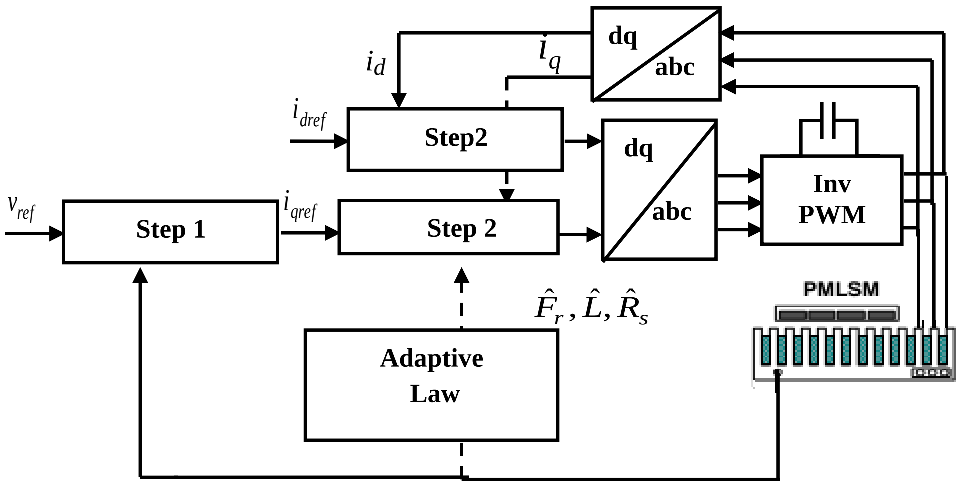

Fig. 1. Block diagram of PMLSM drive using adaptive backstepping control.

Hence the adaptation laws as follows:

TABLE I. PMLSM PARAMETERS

Parameters	Value
Primary Winding Resistance	1.32Ω
Direct-Axis Primary Inductance	11mH
Quadrature-Axis Primary Inductance	11mH
Permanent Magnet Flux	0.65Wb
Mass of the Primary Part	20kg

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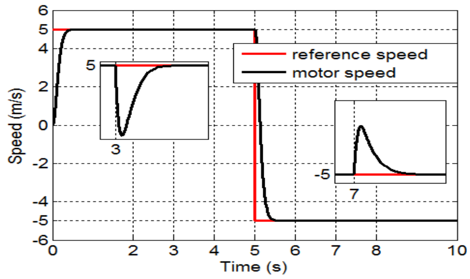
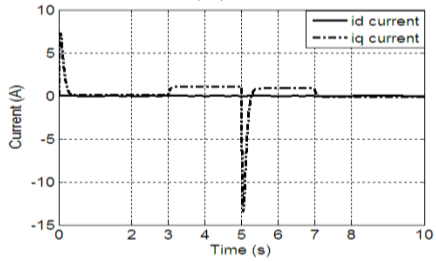
Polar Pitch	30mm
Viscous Damping Coefficient	2Ns/m

Fig. 2 shows the system response when using the proposed nonlinear adaptive Backstepping controller. Reference speed changes from 5m/s with change of direction movement at t=5s. Load force applied is change from 0N to 100N at t=3s and from 100N to 0N at t=7s. The uncertainties of the parametric model are defined as follows during the simulation, the uncertainty term of the stator resistance is increased from 1.32Ω to 2Ω and the stator inductive is increased from 11 mH to 15 mH.

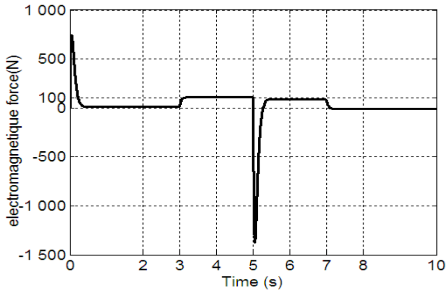
The Fig. 2 (a) indicates the reference linear speed of the motor and the actual linear speed. From Fig. 2 (a), it can be seen that the linear speed of the motor can rapidly track the reference linear speed with small stability error, fast response and small overshoot. Fig. 2(b) shows the variation of electromagnetic force as the load force changes. From Fig. 2(b), it can be seen that the motor has fast force response. Fig. 2(c) shows the wave of rotor current in d-q frame. In Fig. 2(c), d-axis current i_d is zero, which satisfies the control scheme i_d=0 and the q-axis current, i_q is proportional to the load force. Figs.2 (d), 2(e), 2(f) plots the parameter estimations with the actual values of them, in the figs 2(d, e, f) all the parameter estimates converge to their true values and their variations applied.



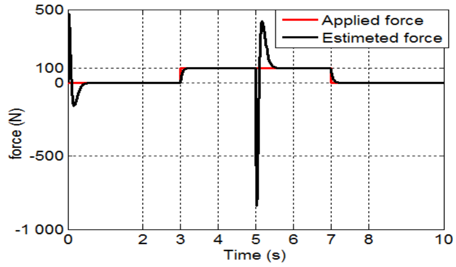
(2a)



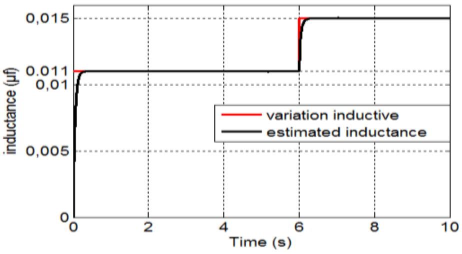
(2b)



(2c)



(2d)



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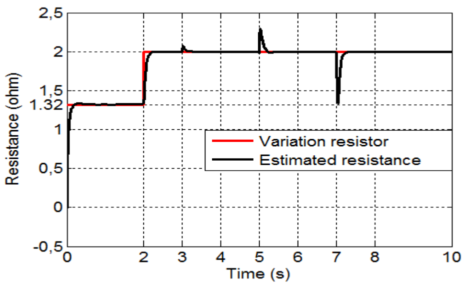

(2f)

Fig. 2. Simulated responses of proposed adaptive backstepping control system due to stepe speed command at case (a) current response. (b) electromagnetic force (c) load force estimated (d) resistance estimated (e) inductance estimated (f).

VI. Conclusion

In this paper, an adaptive backstepping controller is presented in order to accommodate the nonlinearities and uncertainties. The design of backstepping control for the speed control of a PMLSM has been done. The virtual control states of the PMLSM drive have been identified using recursive method and stabilizing laws are developed using Lyapunov stability theory. The proposed controller has been analyzed using MATLAB/Simulink software. The simulation results show its effectiveness at tracking a reference speed under

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parameter uncertainties and nonlinearities, the adaptation law is able to follow the parametric variation. The control strategy is a reliable effective control method.

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