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Design, Modeling, and Simulation of A New Adaptive Backstepping Controller for Permanent Magnet Linear Synchronous Motor: A Comparative Analysis

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ABSTRACT

In this paper, a nonlinear adaptive position controller for a permanent magnet linear synchronous motor based on a newly developed adaptive backstepping control approach is discussed and analyzed. The backstepping approach is a systematic method; it is used for non-linear systems such as the linear synchronous motor. This controller combines the notion of the Lyapunov function, which is based on the definition of a positive energy function; to ensure stability in the sense of Lyapunov, it is necessary to ensure the negativity of this function by a judicious choice of a control variable called virtual control. But this method is mainly based on the mathematical model of the permanent magnet linear synchronous machine (PMLSM) which makes this control sensitive to the variation of the parameters of the machine, to overcome this problem an adaptive control was proposed, the adaptive backstepping control approach is utilized to obtain the robustness for mismatched parameter uncertainties and disturbance load force. The overall stability of the system controller and adaptive low is shown using the Lyapunov theorem. The validity of the proposed controller is supported by computer simulation results.

1. Introduction

With the rapid development of computer technology, electronic technology, and control theory, more and more linear motors are employed in various industrial applications, such as microelectromechanical systems, precision metrology, industrial robots, machine tools, semi-conductor manufacturing systems, etc [1]-[3]. The main features of PMLSM are high force density, low losses, high dynamic performance, fast response, and most importantly, high positioning precision associated with mechanical simplicity. In the last years, there have been numerous progresses in the development of controllers for PMLSMs as listed below [4]-[6].

Ref. [7] used the sliding mode (SM) state observer to replace the speed sensor and the super twisting SM controller (SMC) is used in the loop control of speed and current. The use of high-order SMC features effectively reduces the chattering of the system and reduces the impact of the observation error brought by the observer on the system. To solve the chaotic phenomenon problem in the PMLSM, ref. [8] used a control scheme combining a radial basis function neural network (RBFNN), adaptive backstepping method, and particle swarm optimization (PSO) algorithm. RBFNN identification and PSO optimization have been proposed for PMLSM to get out of chaos. The PSO-RBFNN controller utilized RBFNN to identify the unknown parameters in PMLSM and applied PSO to improve the parameters in the controller. In [9]-[11] a nonlinear robust optimal control (NROC) scheme for an uncertain two-axis motion control system via adaptive dynamic programming (ADP) and NNs has been proposed. The two-axis motion control system is an X-Y table actuated by PMLSM servo drives. The motions of the tracking contour in the X-axis and Y-axis of the X-Y table are stabilized through feedback linearization control (FLC) laws. However, the control performance may be destroyed due to parameter uncertainties and compounded disturbances. Therefore, to improve the robustness of the control system, an NROC has been designed and realized to achieve this purpose.

Ref. [12] developed and realized a new fractional-integral sliding surface. The fuzzy fractional-order SMC has been developed to observe uncertainties, while an adaptive fuzzy reaching regulator is designed to concurrently compensate for observation deviations and suppress the chattering phenomenon. Ref. [13] realized the adaptive backstepping control for the PMLSM servo drive. To overcome the impacts of system uncertainties in the backstepping controller, an adaptive NN has been exploited to estimate the uncertainty and provide necessary compensation in the control effort. Refs. [14]-[16] implemented experimentally the position tracking control of two PMLSMs-based motion control systems. Refs. [17], [18], proposed using an adaptive wavelet NN controller to track periodic reference trajectories by controlling the position of a PMLSM. The adaptive wavelet NN control system makes use of a wavelet NN that can accurately approximate the unknown dynamics of the PMLSM. Additionally, it makes use of a resilient term to address disturbances and the unavoidable approximation mistakes brought on by the finite number of wavelet basis functions.

A robust fuzzy NN-SMC based on computed torque control design for a two-axis motion control system has been presented in [19]-[23]. The two-axis motion control system is an x-y table composed of two PMLSMs. Refs. [24], [25], described and compared three distinct control algorithms: self-tuning adaptive control, model reference adaptive control, and backstepping adaptive control. A reliable nonlinear controller for force and position control of a PMLSM in an extended region has been presented in [26], [27]. To create a robust nonlinear controller that can maintain the drive system's robustness in the face of all parameter variation and uncertainties, an optimal backstepping controller was first designed using an adaptive backstepping control approach. Next, the backstepping control and the artificial neural network were combined, where the artificial NN was used to estimate the complex nonlinear function of the PMLSM in the extended region. Refs. [28]-[31], proposed and realized the observer-based backstepping control of linear stepping motors.

In [32], [33], a hybrid controller for PMLSM using adaptive backstepping SMC was presented. Considering the lumped uncertainties with parameter variations and external disturbances for actual PMLSM drives, a backstepping SMC law was derived by the backstepping design technique. However, the bound of the lumped uncertainty was difficult to obtain in advance in practical applications. An adaptive law was proposed to adapt the value of the lumped uncertainty. The dynamic surface backstepping SM position control method of PMLSM was presented in [34]. Due to the presence of a weakness in a backstepping method that is a complexity of control law caused by achieving the derivation of the virtual control. The dynamic surface control method solved this problem by calculating the derivative of the virtual control using the first-order integral filter [35], [36]. Refs. [37], [38], implemented the adaptive backstepping controller design for a position control system of PMLSM using the digital signal processor. Ref. [39] proposed the sensorless direct thrust force control (DTFC) of PMLSM. A modified stator flux estimator developed by the use of an adaptive mechanism and correction factors is devoted to measuring the stator flux linkage and the mover's position. The parameters of the flux estimator are adjusted in advance through an offline identification process to increase the accuracy of estimation.

Based on the principle of backstepping control and applying the space vector modulation to achieve a fixed switching frequency to have a satisfactory result in all operating conditions, a new adaptive backstepping recursive controller is proposed to overcome the problem of the difficulty in algorithm law, an adaptation law is produced to solve the problem of the backstepping control against the variation of the electrical parameters and the variation of the load force which applied directly to the motor. The backstepping controller is often designed using a recursive method. At first, the authors determine a pseudo-control input for a subsystem with a lower dimension. The next higher-dimensional subsystem appropriate state variable, which is viewed as a fictional control, is controlled to complete the control attempt. Iteratively, the design process continues until the real control input is acquired. For each subsystem, the Lyapunov function is proposed to ensure the stability of the subsystem.

To achieve our objective, this paper is organized as follows: the mathematical model of PMLSM is given in Section 2. The proposed controller and its stability analysis are presented in Section 3. Validation of the proposed controller with PMLSM and discussion of the results are manifested in Section 4, simulation result and discussin in Section 5. General conclusion is presented in Section 6.

2. Mathematic Model of PMLSM

Fig. 1 displays the block diagram of the backstepping position control system for the investigated machine. In addition, the machine parameters are listed in Table 1. The mathematical model of a PMLSM can be described by the following differential equations [34], [40], [41]:

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

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

Where i_d and i_q are the d-axis and q-axis currents, L_d and L_q are the d-an d q-axis inductances, u_d and u_q are the d-axis and q-axis stator voltages, R_s is the stator resistance, φ is the pole pitch, v is the speed, and ψ, is the maximum flux linkage due to permanent magnet in each phase. The electro-mechanical equation of the PMLSM is:

$$F_e = \frac{3\pi}{2\tau M} i_q \left(\psi + \left(L_d - L_q\right) i_d\right) \tag{3}$$

In this paper, the, $L_d = L_q = L$

Then, the mathematical model of PMLSM can be simplified as:

$$\frac{di_d}{dt} = -\frac{R_s}{L} i_d + \frac{\pi}{\tau} v i_q + \frac{1}{L} u_d \tag{4}$$

$$\frac{di_q}{dt} = -\frac{R_s}{L} i_q - \frac{\pi}{\tau} v i_d - \frac{\psi\pi}{L\tau} v + \frac{1}{L} u_q \tag{5}$$

$$\frac{dv}{dt} = \frac{3\pi}{2\tau M} \psi i_q - \frac{F_L}{M} - \frac{B_m}{M} v \tag{6}$$

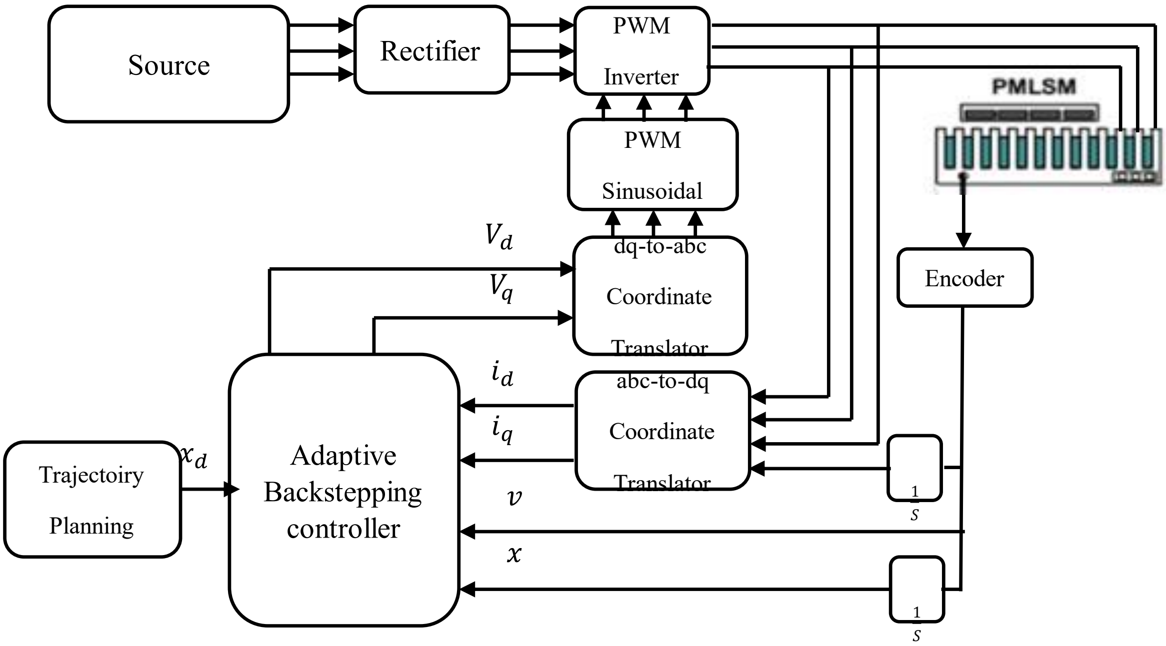

Fig. 1. Block diagram of the backstepping position control system

Table 1. PMLSM system parameters

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
Polar pitch	30mm

3. The Proposed Backstepping Controller Design

This method is applied to systems having a triangular form, as indicated by the following state representation [42]-[44], [23]:

$$\dot{x}_1 = \phi_1^T(x_1) \cdot \vartheta + \psi_1(x_1) \cdot x_2 \tag{7}$$

$$\dot{x}_2 = \phi_2^T(x_1, x_2) \cdot \vartheta + \psi_2(x_1, x_2) \cdot x_3 \tag{8}$$

$$\dot{x}_3 = \phi_3^T(x_1, x_2, x_3) \cdot \vartheta + \psi_3(x_1, x_2, x_3) \cdot u \tag{9}$$

We wish to track the reference signals $\boldsymbol{y_r}$ at the output $y = x_1$where y_r, $\dot{y}_r$, $\ddot{y}_r$ and $y_r^{(3)}$ are considered to be known and uniformly constrained. The system is third-order, and the controller's synthesis is done in three steps.

3.1. First Step

In the first step, the error is defined as:

$$\varepsilon_1 = x_1 - \alpha_0 \tag{10}$$

The dynamic error is defined as follows:

$$\dot{\varepsilon}_1 = \phi_1^T \cdot \vartheta + \psi_1 \cdot x_2 - \dot{\alpha}_0 \tag{11}$$

The proposed Lyapunov function is defined as follows:

$$V_1(\varepsilon_1) = \frac{1}{2}\varepsilon_1^2 \tag{12}$$

Its derivative is given by:

$$\dot{V}_1 = \varepsilon_1\dot{\varepsilon}_1 \tag{13}$$

From equation (11) we obtain:

$$\dot{V}_1 = \varepsilon_1[\phi_1^T \cdot \vartheta + \psi_1 \cdot x_2 - \dot{\alpha}_0] \tag{14}$$

A judicious choice of $x_2$and which makes $\dot{V}_1$ negative and ensures the stability of the origin of the subsystem described by equation (11). Let us take as the value of x_2, the function α_1, such that:

$$\psi_1 \cdot \alpha_1 + \phi_1^T \cdot \vartheta - \dot{\alpha}_0 = -k_1 \cdot \varepsilon_1 \tag{15}$$

Where $k_1 > 0$ is a design parameter, the virtual control is defined as follows:

$$\alpha_1 = \frac{1}{\psi_1}[-k_1 \cdot \varepsilon_1 - \phi_1^T \cdot \vartheta + \dot{\alpha}_0] \tag{16}$$

Where the substitution of equation 16 into 14 we obtain:

$$\dot{V}_1 = -k_1 \cdot \varepsilon_1^2 \leq 0 \tag{17}$$

From the equation (17) we can say that the subsystem is asymptotically stable

3.2. Second Step

In this step, the virtual command from the previous step is chosen as a reference value.

The error is defined as follows:

$$\varepsilon_2 = x_2 - \alpha_1 \tag{18}$$

The equations of the system to be controlled, in space $(\varepsilon_1, \varepsilon_2)$, are written:

$$\dot{\varepsilon}_1 = \phi_1^T\vartheta - \dot{\alpha}_0 + \psi_1(\varepsilon_2 + \alpha_1) \tag{19}$$

$$\dot{\varepsilon}_2 = \phi_2^T\vartheta - \dot{\alpha}_1 + \psi_2 x_3 \tag{20}$$

The proposed Lyapunov function is defined as follows:

$$V_2(\varepsilon_1, \varepsilon_2) = V_1 + \frac{1}{2}\varepsilon_2^2 \tag{21}$$

Its derivative is given by:

$$\dot{V}_2(\varepsilon_1, \varepsilon_2) = \dot{V}_1 + \varepsilon_1\dot{\varepsilon}_2 \tag{22}$$

$$\dot{V}_2(\varepsilon_1, \varepsilon_2) = -k_1\varepsilon_1^2 + \varepsilon_2[\phi_2^T\vartheta + \psi_1\varepsilon_1 + \psi_2 x_3 - \dot{\alpha}_1] \tag{23}$$

The virtual command which ensures the stability of the subsystem is defined as follows:

$$\alpha_2 = \frac{1}{\psi_2}[\dot{\alpha}_1 - \psi_1\varepsilon_1 - \phi_2^T\vartheta - k_2\varepsilon_2] \tag{24}$$

The substitution of equation (24) into (23) we obtain:

$$\dot{V}_2 = -k_1\varepsilon_1^2 - k_2\varepsilon_2^2 \leq 0 \tag{25}$$

From equation (17) we can say that the subsystem is asymptotically stable.

3.3. Third Step

The equations of the system, in the space $(\varepsilon_1, \varepsilon_2, \varepsilon_3)$ given by:

$$\dot{\varepsilon}_1 = \phi_1^T\vartheta - \dot{\alpha}_0 + \psi_1(\varepsilon_2 + \alpha_1) \tag{26}$$

$$\dot{\varepsilon}_2 = \phi_2^T\vartheta - \dot{\alpha}_1 + \psi_2(\varepsilon_3 + \alpha_2) \tag{27}$$

$$\dot{\varepsilon}_3 = \phi_3^T\vartheta - \dot{\alpha}_2 + \psi_3 u \tag{28}$$

In this step, the error is defined as follows:

$$\varepsilon_3 = x_3 - \alpha_2 \tag{29}$$

The dynamic error is defined as follows:

$$\dot{\varepsilon}_3 = \phi_3^T(x_1, x_2, x_3)\cdot\vartheta + \psi_3(x_1, x_2, x_3)\cdot u - \dot{\alpha}_2 \tag{30}$$

In this step the proposed Lyapunov function is defined as follows:

$$V_3(\varepsilon_1, \varepsilon_2, \varepsilon_3) = V_2 + \frac{1}{2}\varepsilon_3^2 \tag{31}$$

Its derivative is given by:

$$\dot{V}_3(\varepsilon_1, \varepsilon_2, \varepsilon_3) = \dot{V}_2 + \varepsilon_3\dot{\varepsilon}_3 \tag{32}$$

From the equations (30), (31) and (32) the equation $\dot{V}_3(\varepsilon_1, \varepsilon_2, \varepsilon_3)$ is given as follows:

$$\dot{V}_3(\varepsilon_1, \varepsilon_2, \varepsilon_3) = -k_1\varepsilon_1^2 - k_2\varepsilon_2^2 + \varepsilon_3[\psi_3 u + \psi_2\varepsilon_2 + \phi_3^T\vartheta - \dot{\alpha}_2] \tag{33}$$

The control law to ensure the stability of the third subsystem and the global system is given by:

$$u = \frac{1}{\psi_3}[\dot{\alpha}_2 - \psi_2\varepsilon_2 - \phi_3^T\vartheta - k_3\varepsilon_3] \tag{34}$$

Where k_1, $k_2$and $k_3$they are positive constants.

The substitution of equation (34) in (33) we obtain:

$$\dot{V}_3 = -k_1\varepsilon_1^2 - k_2\varepsilon_2^2 - k_3\varepsilon_3^2 \leq 0 \tag{35}$$

4. Design of the Backstepping Adaptive Controller

The structure of the recursive backstepping controller proposed for the position control of PMLSM is a cascade control, that divides the position control loop into three steps. In the first step we controlled the position, we chose the movement speed as a virtual variable to ensure the stability of the sub-system or the error position and it's chosen in the next step or the second step as a quantity to be controlled. In the second step, we chose the dq currents as a virtual control to ensure the stability of the sub-system or the error speed and they chose in the next step or the third step as a quantity to be controlled. In the third step to ensure the stability of the sub-system or the current errors, we chose the voltages as a virtual control. For each step, we proposed a Lyapunov function to ensure the stability of each sub-system and a global function in the last step to ensure the overall stability of the system. The dynamic equation is simplified as:

$$\frac{dv}{dt} = Ai_q - \frac{F_L}{M} - \frac{B_m}{M}v$$
$$A = \frac{3\pi}{2\tau M}\psi \quad (36)$$

4.1. Step 1

For PMLSM position control, the control objectives are mainly location tracking. In this step the position tracking error is as follows:

$$e_1 = x^* - x \quad (37)$$

Where x^* end x is the position of reference and the position actual. The dynamics of this error $\dot{e}_1$ is:

$$\dot{e}_1 = \dot{x}^* - v \quad (38)$$

The first positive Lyapunov function can be defined as follows:

$$V_1 = \frac{1}{2}e^2 1 \quad (39)$$

The time derivative of V_1 is given, after some mathematical manipulation, in the following

$$\dot{V}_1 = e_1\dot{e}_1 = e_1(\dot{x}^* - v) \quad (40)$$

$v^* = \dot{x}^* + k_1 e_1$ With $k_1 > 0$

4.2. Step 2

Now we define the speed tracking error as

$$e_2 = v^* - v = x^* + k_1 e_1 - v \quad (41)$$

From equation (12) we have defined the dynamic error of position as:

$$\dot{e}_1 = -k_1 e_1 + e_2 \quad (42)$$

Take the derivation of the velocity tracking error e_2 and express the result as

$$\dot{e}_2 = \ddot{x}^* + k_1(-k_1 e_1 + e_2) - Ai_{qs} + \frac{F_L}{M} - \frac{B_m}{M}v \quad (43)$$

Now define q new Lyapunov function as

$$V_2 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 \quad (44)$$

Differentiate to get

$$\dot{V}_2 = e_1\dot{e}_1 + e_2\dot{e}_2 \; \dot{V}_2 = -k_1 e_1^2 - k_2 e_2^2 + e_2 \begin{bmatrix} e_1(1 - k_1^2) + k_1 e_2 + \ddot{x}^* - Ai_{qs} \\ + \frac{F_L}{M} + \frac{B_m}{M}v + k_2 e_2 \end{bmatrix} \quad (45)$$

With $k_2 > 0$

Since i_{ds} and i_q were identified as the virtual control variable we define reference current as:

$$\begin{cases} i_{ds} = 0 \\ i_{qs} = \frac{1}{A} \left[(1 - k_1^2)e_1 + (k_1 + k_2)e_2 + x + \frac{F_L}{M} + \frac{B_m}{M} v \right] \end{cases} \tag{(46)}$$

The parameters that must be estimated here are the inductance L which varies with magnetic saturation, stator resistance R_s which varies with temperature, and load torque $\hat{F}_L$ which sometimes cannot be measured directly. The corresponding error variables are given by $\hat{L} = L + \tilde{L}, \hat{R}_s = R_s + \tilde{R}_s, \hat{F}_L = F_L + \tilde{F}_L$.

4.3. Step 3

The object now is to make and follow the reference trajectory end of the final current error signal is defined as:

$$e_3 = i_{qs}^* - i_{qs} \tag{47}$$

$$e_4 = i_{ds}^* - i_{ds} \tag{48}$$

Using equations (47) and (48) the speed error dynamics can be represented by

$$\dot{e}_2 = Ae_3 - e_1 - k_2 e_2 - \frac{\tilde{F}_L}{M} \tag{49}$$

Now we defined the current error dynamics as

$$\begin{aligned} \dot{e}_3 &= \dot{i}_{qs}^* - \dot{i}_{qs} \\ \dot{e}_4 &= \dot{i}_{ds}^* - \dot{i}_{ds} \end{aligned} \tag{50}$$

$$\begin{aligned} \dot{e}_4 = -\phi - \frac{U_d}{L_d} \ \dot{e}_3 &= \frac{1}{A}[(1 - k_1^2)(e_2 - k_1 e_1) + (k_1 + k_2) \\ (A_{e_3} - e_1 - k_2 e_2 &- \frac{\tilde{F}_L}{M} + \dddot{x}^* - \frac{\dot{\hat{F}}_L}{M} - \frac{\hat{B}_m}{M}\dot{v}] - \phi_1 - \frac{U_q}{L} \end{aligned} \tag{51}$$

$$\dot{e}_4 = -\phi_2 - \frac{U_d}{L_d} \tag{52}$$

Where

$$\phi_1 = -\frac{R_s}{L} i_q - \frac{\pi}{\tau} v i_d - \frac{\psi\pi}{L\tau} v \tag{53}$$

$$\phi_2 = -\frac{R_s}{L} i_d - \frac{\pi}{\tau} v i_q \tag{54}$$

The last positive definite Lyapunov function can be to ensure the stability of the control system and to determine the parameter adaptation laws.

$$V_3 = \frac{1}{2}(e_1^2 + e_2^2 + Le_3^2 + Le_4^2 + \frac{1}{n_1}\tilde{F}_L^2 + \frac{1}{n_2}\tilde{R}_s^2 + \frac{1}{n_3}\tilde{L}^2 \tag{55}$$

Where n_1, n_2 and n_3 are the positive finite adaptation gains. The derivative is expressed as:

$$\dot{V}_3 = e_1\dot{e}_1 + e_2\dot{e}_2 + Le_3\dot{e}_3 + L_{e_4}\dot{e}_4 + \frac{1}{n_1}\tilde{F}_L\dot{\tilde{F}}_L + \frac{1}{n_2}\tilde{R}_s\dot{\tilde{R}}_s + \frac{1}{n_3}\tilde{L}\dot{\tilde{L}} \tag{56}$$

The time derivative of the desired q end d axis current in the third Lyapunov function of (56) is expressed under the assumption (4), (5) as the following:

$$\begin{gathered}\dot{V}_3 = e_1(-k_1e_1 + e_2) + \left(Ae_3 - e_1 - k_2e_2 - \frac{\tilde{F}_L}{M}\right) \\ +e_3\left[L/A\left[(1-K_1^2)(e_2 - k_1e_1) + (k_1+k_2)\left(Ae_3 - e_1 - k_2e_2 - \frac{\tilde{F}_L}{M}\right) + \dddot{x}^* + \frac{\dot{\hat{F}}_L}{M} + \frac{B_m}{M}\dot{v}\right] + R_si_q \right. \\ \left. + \frac{L\pi}{\tau}vi_d + \frac{\psi\pi}{\tau}v - U_q\right] + e_4\left[R_si_d - i_d - L\frac{\pi}{\tau}vi_q - U_d\right]\end{gathered} \tag{57}$$

To ensure the stability of the system controlled and estimate the stator resistance, inductance, and load force the function $\dot{V}_3$ it gives as follows:

$$\begin{gathered}\dot{V}_3 = -k_1e^21 - k_2e^22 - k_3e^23 - k_4e^24 + e_2\left(-\frac{\tilde{F}_L}{M}\right) \\ +e_3\left[k_3e_3 + (\hat{L}-\tilde{L})/A\left[(1-K_1^2)(e_2-k_1e_1) + (k_1+k_2)\left(Ae_3 - e_1 - k_2e_2 - \frac{\tilde{F}_L}{M}\right) + \dddot{x}^* + \frac{\dot{\hat{F}}_L}{M} + \frac{B_m}{M}\dot{v}\right] + Ae_2 \right. \\ \left. + (\hat{R}_s - \tilde{R}_s)i_q + \frac{(\hat{L}-\tilde{L})\pi}{\tau}vi_d + \frac{\psi\pi}{\tau}v -_q\right] + e_4\left[k_4e_4 + (\hat{R}_s - \tilde{R}_s)i_d - (\hat{L}-\tilde{L})\frac{\pi}{\tau}vi_q - U_d\right]\end{gathered} \tag{58}$$

The d-q axis reference voltages are chosen to be:

$$\begin{gathered}U_q = k_ee_3\hat{L}/A\left[(1-k_1^2) + (k_1+k_2)(Ae_3 - e_1 - k_2e_2) + \dddot{x}^* + \frac{\dot{\hat{F}}_L}{M} + \frac{B_m}{M}\dot{v}\right] \\ Ae_2 + \hat{R}_si_q + \frac{L\pi}{\tau}vi_d + \frac{\psi\pi}{\pi}v\end{gathered} \tag{59}$$

$$U_d = k_4e_4 + \hat{R}_si_d - L\frac{\pi}{\tau}vi_q \tag{60}$$

The updated laws are defined as:

$$\dot{\hat{F}}_L = n_1\left(\frac{e_2}{M} + \frac{L}{AM}(k_1+k_2)e_3\right) \tag{61}$$

$$\dot{\hat{R}}_s = n_2(e_3i_q + i_de_4) \tag{62}$$

$$\begin{gathered}\dot{\hat{L}} = n_3\left(\frac{e_4\pi}{\tau}vi_q - \frac{e_3\pi}{\tau}vi_d - \left(\frac{e_3}{A}\right)\right. \\ \left.\left[(1-k_1^2)(e_2 - k_1e_1) + (k_1-k_2)(Ae_3 - e_1 - k_2e_2) + \dddot{x}^* + \frac{\dot{\hat{F}}_L}{M} + \frac{B_m}{M}\dot{v}\right]\right)\end{gathered} \tag{63}$$

5. Simulation Results and Discussion

5.1. Case 1

For triangular reference and 10 s simulation time, the performances of the controller are examined in detail under the load force disturbance variation for the whole operating range. The load force applied to PMLSM is 100 Nm.

The dynamic position tracking responses of the control systems corresponding to the reference triangular conditions are given in Fig. 2 a–h. The reference position trajectory and actual position are in Fig. 2 a this figure demonstrates that the asymptotic position objective is achieved with high accuracy, the speed, d-q axis stator currents, and electromagnetic force are shown in Fig. 2 (b, c, d, and e) respectively, from this figures it is observed that the q-axis stator current is directly proportional to the electromagnetic force, and d-axis stator current should be zero, and that the speed necessary for a distance of 0.1m is 0.5m / s, Fig. 2 (f, g, and h) plots the parameter estimations, load force applied, stator resistance, and stator inductance with the actual values of them. As can be observed, all parameter estimates converge to their true values.

5.2. Case 2

Starting with no load with the application of a load disturbance at time 3s and no load in 5s, with a triangular reference position and the disturbance parameters at time 7s for the resistance 1.32 Ω to 2 Ω and the inductance at time 9s $11_e - 3H$ to $15_e - 3H$.

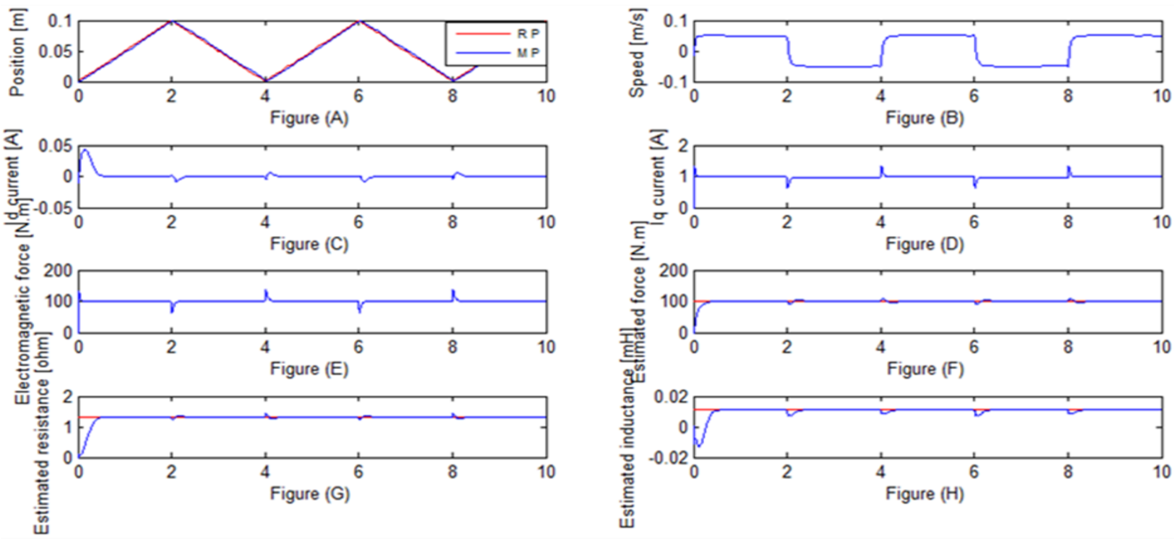

Fig. 2. Simulated results for the condition of case 1

Table 2. Comparison of the proposed adaptative backstepping controller method with previously published controllers

Ref,	Controller type	Adaptative parameters	Performance	Transient response	Complexity
[45]	PID	×	Poor	Low	Low
[41], [46]	Fuzzy PID	×	Good	High	Low
[8], [47]	SMC	×	Good	High	Low
[8]	Backstepping	×	Good	High	Low
[48]	Feedback linearization	×	Good	High	low
[49], [50]	Adaptive terminal SMC	✓	Very good	High	High
[13]	Adaptive backstepping	✓	Good	High	High
[34]	Dynamic surface backstepping SM	×	High	High	Low
[51]	Adaptive NN nonsingular fast terminal SMC	✓	Very high	High	High
Proposed adaptative backstepping controller		✓	High	High	Low

Fig. 3 (a) plots the reference trajectory and actual position; it's observed that the actual position follows the reference with good accuracy. In Fig. 3 b, plotting the motor speed, it is observed that the speed necessary for a distance of 0.1 m is 0.5 m/s. The stator current components and the electromagnetic force are shown in Fig. 3 (c, d, and e) it is shown that the q-axis stator current is directly proportional to the electromagnetic force, and the d-axis stator current should be zero. All the parameter estimations are given in Fig. 3 (f, g, and h), which reflect that all the parameter estimations converge to their true values.

Through the comparison completed in Table 2, it can be said that all intelligent and advanced control methods are good, but the difference remains in the method of design of the controller, and the advantage of the proposed control remains in the number of parameters that have been estimated in the system that depends on controlling the position of the motor.

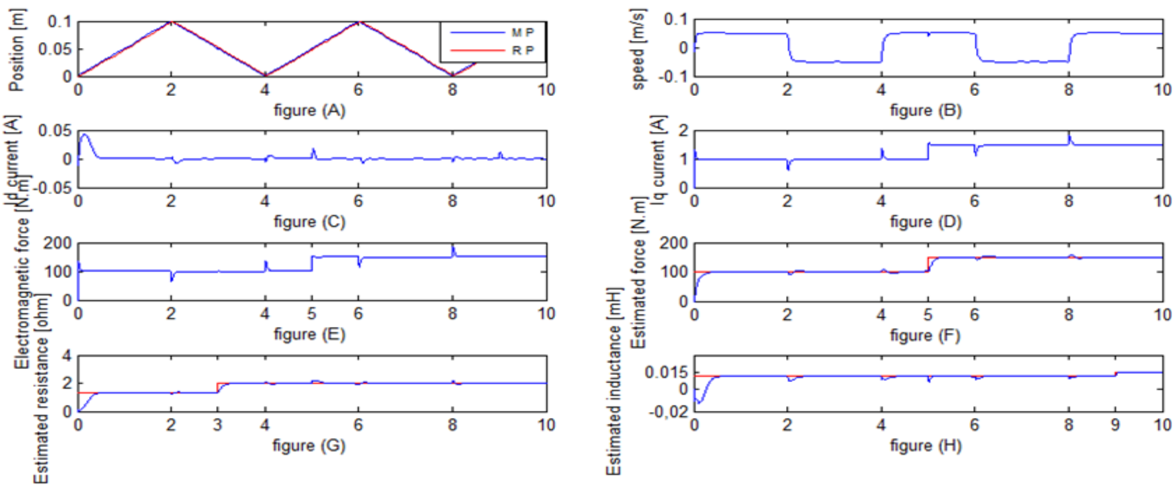

Fig. 3. Simulated results for the condition of case 2

6. Conclusions

In this paper, a nonlinear adaptive controller has been proposed for tracking the position of a PMLSM which operates in various conditions. The nonlinear controller has been designed based on adaptive backstepping recursive position controls the overall stability of this system according to the Lyaponuv theory, the problem of parameter insertion and disturbing load is solved according to the adaptive law. From the simulation results, it was found that the proposed controller is robust and could be a potential candidate for use in high-performance industrial drive applications.

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