

International Conference on Manufacturing Engineering and Intelligent Materials (ICMEIM 2017)

Adaptive Nonlinear Control for Linear Induction Motor Based on Q-Axis Current Compensation

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Keywords: Linear Induction Motor, Adaptive Control, Command-filtered Back Stepping.

Abstract. The aim of paper is to propose position control of linear induction motor (LIM) taking into account the end effect, external force disturbance and the uncertainties of LIM model by use of an adaptive command-filtered back stepping controller based on q-axis current compensation to improve the dynamic performance and robustness of controlled system. Two simulation cases are carried out to demonstrate the possibility and effectiveness of proposed controller.

Introduction

LIM is a kind of driving device with excellent performance, which does not need the intermediate transmission device and produce linear motion thrust directly compared with the rotary induction motor [1-3], which has been widely used in industrial machine, transportation, military and other fields. However, the parameters of LIM are time-varying and uncertain 0. So, the exact model of LIM is difficult to obtain, and advanced and effective control scheme need to be studied.

In the control method, backstepping is easy to combine with adaptive control technique [1], which can eliminate the influence of parameter variation and external disturbance, so it has been applied in control of LIM so that satisfactory control performance is obtained [1-2]. Furthermore, the essence of adaptive law for motor parameters is to compensate the q-axis controller current so as to achieve the purpose of current tracking. So, in this paper, we design to compensate the q-axis control current directly in the velocity tracking error, which avoids the complex calculation of the adaptive law for each uncertain parameter.

The rest of the paper is organized as follows. In section 2, model of LIM considering the end effect is described. In section 3, the design process and stability analysis of proposed control scheme has been presented step by step. In section 4, simulation results are shown to demonstrate the possibility and effectiveness of the designed controller. Finally, some conclusions are discussed in Section 5.

Model of LIM Considering End Effect

By use of the indirect vector control, the rotor flux linkage is oriented to the d-axis and model follows that $\phi_{qr} = \dot{\phi}_{qr} = 0$, $\phi_{dr} = \phi_r = 0$.

So, LIM model of indirect vector control [3-4] is expressed as follows

$$\dot{i}_{ds} = -\frac{R_s}{L(Q)} \dot{i}_{ds} + \frac{V_{ds}}{L(Q)} + \omega_e \dot{i}_{qs}, \quad \dot{i}_{qs} = -\omega_e \left[i_{ds} + \frac{L_m \left(1 - f(Q) \right)}{L(Q) \left(L_r - L_m f(Q) \right)} \phi_{dr} \right] - \frac{R_s}{L(Q)} \dot{i}_{qs} + \frac{V_{qs}}{L(Q)}, \\ \phi_{dr} = \frac{L_m \left[1 - f(Q) \right]}{1 + \left[T_r - L_m f(Q) / R_r \right]} \dot{i}_{ds}, \quad \omega_{sl} = \frac{L_m \left[1 - f(Q) \right]}{T_r - L_m f(Q) / R_r} \frac{\dot{i}_{qs}}{\phi_{dr}}, \quad F_e = K_T \dot{i}_{qs} = M \cdot \dot{v} + B \cdot v + F_L,$$
(1)

$$T_{r} = L_{r} / R_{r}, f(Q) = (1 - e^{-Q}) / Q, K_{T} = \frac{3}{2} P \frac{\pi}{h} \frac{L_{m} (1 - f(Q))}{L_{r} - L_{m} f(Q)} \phi_{dr}, L(Q) = L_{s} - L_{m} f(Q) - \frac{\left[L_{m} (1 - f(Q)) \right]^{2}}{L_{r} - L_{m} f(Q)}$$



where i_{ds} and i_{qs} are the d-q axis primary current; R_s and R_r are the primary and secondary resistance; ω_e and ω_r are the stator and rotor angular frequency; ϕ_{dr} is the d-axis secondary flux linkage; L_m is the magnetizing inductance; L_s is the primary inductance; L_r is the secondary inductance of the LIM; M is the total mass of moving element; B is the viscous friction; F_L is the external force disturbance; F_e is the electromagnetic thrust; T_r is the secondary time constant; P is the number of pole-pairs; h is the pole pitch; v is the mover speed of LIM.

Design and Stability Analysis of Adaptive Nonlinear Control

LIM has typical nonlinearity and the control parameters may not be known accurately. In addition, the model parameters of LIM may change because of the environment called model uncertainty, which seriously affects the control performance of the LIM, so the purpose of this paper is to design an appropriate controller to achieve good performance under the condition that the model parameter is uncertainty and the motor parameter is fluctuation.

In order to achieve the accurate position control of the LIM, an adaptive command-filtered backstepping control based on q-axis current compensation has been designed for LIM considering end effect. In addition, the mover speed of LIM v and q-axis primary current i_{qs} are also chosen as control variable, meanwhile the tracking errors e_1 , e_2 and e_3 are defined as follows:

$$e_1 = d - d_c, \ e_2 = v - v_c, \ \dot{e}_3 = i_{qs} - i_{qsc},$$
 (2)

where d_c is the desired position command, v_c and i_{asc} are the output of the command filter.

Then, the design process of proposed controller is derived step buy step as follows:

Step 1: we consider the Lyapunov function for position loop control as $V_1 = e_1^2 / 2$, Then, the time derivative of V_1 can be computed as

$$\dot{V}_{1} = e_{1}\dot{e}_{1} = e_{1}\left(v - \dot{d}_{c}\right) = -k_{1}e_{1}^{2} + e_{1}\left(k_{1}e_{1} + v - \dot{d}_{c}\right),$$
(3)

To make that $\dot{V} \leq 0$, the virtual controller of position loop can be designed as $v_d = \dot{d}_c - k_1 e_1$, where v_d is the reference velocity, $k_1 > 0$ is a design constant. Therefore, the designed virtual controller is asymptotically stable according to Lyapunov stability theory.

Pass the v_d through the constrained command filter (see in Fig. 1) [1], we can achieve the filtered command v_c and its time derivative \dot{v}_c . The error $\mu = v_c - v_d$ can be adjusted by bandwidth ω_n .

The filtering error generated by command filter is solved by redefined tracking error as $\overline{e_1} = e_1 - \varepsilon_1$, and a compensating signal is considered as $\dot{\varepsilon}_1 = -k_1\varepsilon_1 + (v_c - v_d)$.

Step 2: In order to get the speed loop virtual controller, the Lyapunov function is defined as

$$V_2 = \frac{1}{2}\overline{e_1}^2 + \frac{1}{2}e_2^2, \tag{4}$$

Then, the time derivative of V_2 can be calculated as



$$\dot{V}_{2} = -k_{1}\overline{e}_{1}^{2} - k_{2}e_{2}^{2} + e_{2}\left(\frac{K_{T}}{M}i_{qs} + Dv + F - \dot{v}_{c} + k_{2}e_{2} + \overline{e}_{1}\right),$$
(5)

The virtual control of speed loop can be selected as

$$i_{qsd}^{1} = \frac{M}{K_{T}} \left(\dot{v}_{c} - Dv - F - k_{2}e_{2} - \overline{e}_{1} \right), \qquad (6)$$

Where $k_2 > 0$ is a design constant, the we can get $\dot{V}_2 = -k_1 \overline{e_1}^2 - k_2 e_2^2 \le 0$. We design to compensate the q-axis control current directly in the velocity tracking error.

We design to compensate the q-axis control current directly in the velocity tracking error. According to (6), the i_{qsd} can be designed as

$$i_{qsd} = \frac{M}{K_T} \left(\dot{v}_c - Dv - F - k_2 e_2 - \overline{e_1} - \eta \right), \tag{7}$$

where η is compensation signal of q-axis control current. Then, the tracking error is redefined as $\overline{e}_2 = e_2 - \varepsilon_2$ and its compensating signal is $\dot{\varepsilon}_2 = -k_2\varepsilon_2 + (i_{qsc} - i_{qsd}) \cdot K_T / M$.

Step 3: To achieve the controller and adaptive law, third step Lyapunov function is defined as

$$V_{3} = \frac{1}{2} \left(\overline{e_{1}}^{2} + \overline{e_{2}}^{2} + e_{3}^{2} + \frac{\eta^{2}}{k_{4}} \right),$$
(8)

Finally, the time derivative of V_3 can be calculated as

$$V_{3} = -k_{1}\overline{e_{1}}^{2} - k_{2}\overline{e_{2}}^{2} - k_{3}e_{3}^{2} + \overline{e_{1}}\varepsilon_{2} + \eta \left(\frac{\dot{\eta}}{k_{4}} - \overline{e_{2}}\right) + e_{3}\left[X + \frac{V_{qs}}{L(Q)} - \dot{i}_{qsc} + k_{3}e_{3}\right],$$
(9)

where X is a known signal and expressed as $X = -\omega_e \left(i_{ds} + \frac{L_m (1 - f(Q))}{L(Q) (L_r - L_m f(Q))} \phi_{dr} \right) - \frac{R_s}{L(Q)} i_{qs}$. So the control law and adaptive law can be designed as

$$V_{qsd} = L(Q) \left(\dot{i}_{qsc} - X - \frac{K_T}{M} \overline{e}_2 - k_3 e_3 \right), \quad \dot{\eta} = k_4 \overline{e}_2$$

$$, \qquad (10)$$

If $|\overline{e_1}| \varepsilon_2 - k_1 \alpha \overline{e_1}^2 \le 0$, i.e., $|\overline{e_1}| \ge \frac{\varepsilon_2}{k_1 \alpha}$, and let $0 < \alpha < 1$, then $\dot{V_3}$ becomes:

$$V_3 \leq -k_1 (1-\alpha)\overline{e_1}^2 - k_2\overline{e_2}^2 - k_3 e_3^2 \leq 0, \quad \forall |\overline{e_1}| \geq \frac{\varepsilon_2}{k_1 \alpha}.$$

$$(11)$$

Therefore, whole system are uniformly ultimately bounded 0. To give a clear understanding of the overall proposed controller, the control block diagram is shown in Fig. 2.



Figure 1. Structure of command filter



Figure 3. simulation result of case 1





Figure 4. simulation result of case 2

Simulation Study

In this section, two cases are carried out to demonstrate the effectiveness of the designed controller. The parameters of LIM in reference 0 and the constrained command filter [1] are used in this paper. In addition, the controller parameters are chosen as $k_1 = k_2 = k_3 = 50$ and the adaptive law is selected as $k_4 = 5e + 5$, which is used to obtain a good control performance.

In case 1, the proposed adaptive command-filtered backstepping controller (ACBC) based on q-axis current compensation is compared with the conventional PID controller under the condition of periodic external force disturbance $F_L = 30 \sin(2\pi t)$; in case 2, the ACBC based on q-axis current compensation is compared with the traditional command-filtered backstepping controller (CBC) under the condition of the variation of the LIM parameters, i.e., $R'_s = 1.5R_s$ and M' = 2M. The simulation results of case1 and case 2 are displayed in Fig. 3 and Fig. 4, respectively.

From the simulation results of case 1, we can find that the proposed ACBC has stronger anti-interference and better dynamic performance compared with PID controller. In addition, from the Fig. 4, the robustness of control system is much improved by proposed ACBC compared with the conventional CBC under the condition of uncertainty and variation of LIM parameters.

Conclusion

This paper has proved the application of an adaptive nonlinear control to the position control of a LIM considering the end effect, external force disturbance and the model uncertainties. First, the dynamic model of LIM taking into account the en effect is described. Then, command filter is applied in traditional backstepping, which solves the problem of input saturation and explosion of complexity. Meanwhile, a filter-compensation signal is designed to compensate the filtering error caused by



command filter. Next, we design to compensate the q-axis control current directly in the velocity tracking error, which improves the dynamic and static performance and avoids the complex calculation of the adaptive law simultaneously for each uncertain parameter. Moreover, the stability of the whole system has been proved by Lyapunov stability theory. Finally, the simulation results proved that the designed controller has stronger anti-interference and better dynamic performance compared with PID controller and more robust than conventional CBC under the condition of uncertainty and variation of LIM parameters.

Acknowledgement

This research was supported by National Natural Science Foundation of China (61503156, 51405198) and the Fundamental Research Funds for the Central Universities (JUSRP11562, JUSRP51406A, NJ20150011) and National Key Research and Development Program (2016YFD0400300) and the Science and Technology Funds for Jiangsu China (BY2015019-24).

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