International Journal of Control and Automation
Vol.7, No.6 (2014), pp.325-338
http://dx.doi.org/10.14257/ijca.2014.7.6.30

A DSP-based Robust Position Controller of a Single-sided Linear Induction Motor for Automatic Picking System

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Abstract

For application of a single-sided linear induction motor (LIM) to an automatic picking system (APS), this paper presents a DSP-based robust position controller design using an integral sliding mode control (SMC) scheme. To operate a movable ejector in the APS with high precision and high dynamics, a high performance linear motor drive system is required. The force disturbance as well as the mechanical parameter variations such as the mass and friction coefficient influence directly on the position control performance of APS. To guarantee a robust control performance in the presence of such uncertainty, an integral SMC-based position controller is considered. A Simulink library is developed for the LIM dynamic model. The entire system is realized using DSP TMS320F28335 based controller for performance comparison. Using the comparative simulations based on Matlab – Simulink and experiments, the effectiveness of the proposed scheme is verified. As a result, the proposed scheme has a robust control nature and is most suitable for an implementation of the APS.

Keywords: *APS, DSP TMS320F28335, Integral sliding mode control, Linear induction motor, Robust position control*

1. Introduction

To cope with a recent environmental change in the distribution industry as well as a change in consumer's spending pattern, many interests have been focused on the development of the advanced distribution system such as an automatic picking system (APS) which can effectively handle the order in small and diverse products [1-2]. While the early technology is to combine a conventional rotary motor coupled with mechanical transducers such as the ball screw, gear, and chain, a direct adoption of a linear motor technology with high efficiency and reduced mechanical stress has been developed recently. For this reason, a linear driving mechanism with high accuracy has been recognized as an essential component to realize a movable ejector in the APS. A linear motor develops the linear driving force directly without using any mechanical transducers. Furthermore, it has the advantages of simple structure, reduced energy loss, and low noise due to the absence of mechanical transducers.

ISSN: 2005-4297 IJCA

To implement a movable ejector in the APS with high precision and high dynamics using the linear motor, an issue on the design of a high performance linear motor drive system has become a major concern in the related fields. Along with this issue, a high performance and robust position controller design in linear motion system has been an important topic. Recently, several works have been studied to control the position of a linear induction motor (LIM) as a single unit without considering the APS [3-4]. However, the scheme in [4] is too complex to apply in the physical APS. Even though the compensation methods using a model reference adaptive control or the load torque observer have been developed to improve the control performance [5-6], they work well only when the variation of an unknown disturbance is not large during sampling interval. Using these approaches, it is difficult to estimate the parameter variation effect because some parameter mismatch like the mass produces a disturbance proportional to acceleration.

In this paper, a high performance robust position controller design of a single-sided LIM for an APS using the integral sliding mode control (SMC) is presented, which can operate the movable ejectors of the APS with high dynamics and high precision in the stage of the pickup, transportation, and sorting of logistics. First, the entire LIM drive system is implemented through the voltage source inverter and a field-oriented control using the indirect method. Based on this system, a robust position controller is designed using the mechanical dynamics. The proposed scheme is achieved by the integral SMC [7-8] to guarantee a robust and accurate response by applying the discontinuous control input through switching logic. To verify that the proposed scheme has a robust control nature and is most suitable for the APS, the comparative simulations are carried out using Matlab - Simulink. Since Simulink does not support the library for the LIM, a Simulink library model for the LIM has been developed using the LIM dynamic model. The whole control system is implemented using DSP TMS320F28335 for a LIM driven by a three-phase voltage-fed PWM inverter.

2. Modeling of LIM

The structure of a single-sided three-phase LIM is shown in Figure 1, which is composed of the primary and secondary sides [9]. Three-phase windings with sinusoidal distribution are placed on the primary side similar to the stator of a rotary motor. The secondary side consists of a sheet conductor with a back iron for the return path of the magnetic flux.

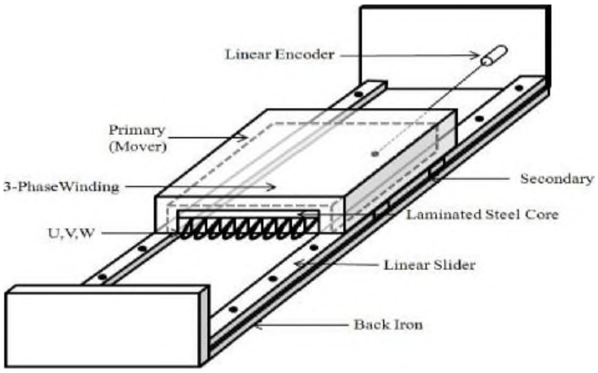


Figure 1. Configuration of a LIM

The field-orientated control is generally employed to decouple the dynamics of the thrust force and the flux amplitude of the LIM [10, 11]. The stator and rotor voltage equations of the LIM in the synchronously rotating reference frame are described through the modification of the traditional rotary induction motor as follows [4]:

(1)

(2)

(3)

—— (4)

where v_{qs} is the q-axis primary voltage, v_{ds} is the d-axis primary voltage, v_{qr} is the q-axis secondary voltage, v_{dr} is the d-axis secondary voltage, R_s is the primary resistance, R_r is the secondary resistance, i_{qs} is the q-axis primary current, i_{ds} is the d-axis primary current, i_{qr} is the q-axis secondary current, i_{dr} is the d-axis secondary current, p is the differential operator, $\boldsymbol{2}_{qs}$ is the q-axis primary flux, $\boldsymbol{2}_{ds}$ is the d-axis primary flux, $\boldsymbol{2}_{qr}$ is the q-axis secondary flux, $\boldsymbol{2}_{dr}$ is the d-axis secondary flux, v_e is the synchronous linear velocity, v_{sl} is the linear slip velocity, and h is the pole pitch.

From the stator and rotor voltage equations in (1)-(4), the state equations can be obtained by taking the state variables as i_{qs}, i_{ds}, $\boldsymbol{2}_{qr}$, and $\boldsymbol{2}_{dr}$. Using these state equations, a Matlab - Simulink model for the LIM can be constructed. The developed Simulink model block for the LIM is shown in Figure 2.

$$s \square x_2 + \square x_1 + c \square\square\square_t x_1 d \square$$

3. Robust Position Controller

The thrust equation of the LIM is expressed as follows:

(5)

where K_t is the thrust constant, M is the mass of the mover, D is the friction coefficient, v_m is the linear velocity, and F_L is the external thrust disturbance. To ensure a robust position control performance of the APS in the presence of the variation of mechanical parameters, the position controller for the LIM is designed based on the integral SMC, which consists of an equivalent control input and a switching control input. In this paper, the variations of the mass, friction coefficient, and external thrust disturbance are considered for the mechanical parameter variation.

A sliding surface of the integral SMC can be defined as follows:

$$0 \qquad (6)$$

where x_1 is the position error of the mover and x_2 is the speed error. They are defined as

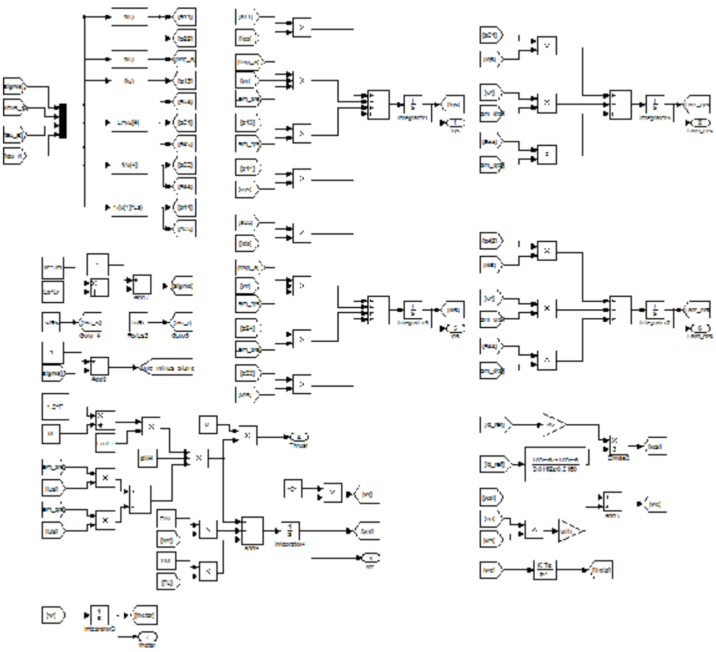


Figure 2. Developed Simulink Model for the LIM

M

eq_K □ o □ x_2 $x_2 cx_1$ □

M □

(7)

(8)

where the symbol "*" denotes the reference quantities and d_m is the position of the mover. Using (6), the dynamic characteristics of the control system on the sliding surface can be easily assigned by □, c and the initial value of integrator. The initial value of integrator should be set at t=0 to generate the sliding mode even during the whole transient period. This initial value can be obtained from (6) by substituting t=0 as

□ K

K d

(9)

where I_o denotes the initial value of integrator. The equivalent control input u_{eq} can be obtained from (6) from the conditions of f=0 and as

$$\square \; u \; \square^{o} \quad \square \; \square_{o} \, \mathrm{sgn}(s) \; \square^{o} \quad \square\square$$

.

The switching control input to maintain the states on the sliding surface is a discontinuous function and can be expressed as follows:

(11
)

s□

where □ is the gain of switching function and sgn(s) is the sign function. From the sliding mode existence condition , □ can be obtained as follows:

(10
)

u

M M s

s

p .

(12)

λ

1

min

.

M

0

1

The switching control input generally produces a large chattering in the system because it includes the discontinuous component due to sign function on the sliding mode. To alleviate this chattering, the switching function is changed to a continuous function instead of the discontinuous function as follows:

(13)

4. Configuration of the System

Figure 3 shows the configuration of the DSP controller. The whole control algorithms are implemented using 32-bit floating-point DSP TMS320F28335 with 150MHz clock [12]. DSP TMS320F28335 has 256K word of on-chip flash memory and some peripherals such as an internal 12-bit AD converter and 16-bit PWM port. The sampling period is set to 100 [μsec], which yields a switching frequency of 10 kHz in the PWM inverter. The reference voltages are applied through the symmetrical space vector PWM technique. The mover speed and position are detected through a linear encoder and processed in the internal DSP module with the resolution of 2μm. The phase currents and voltages are detected by the sensors and fed to DSP using the internal 12-bit A/D converter.

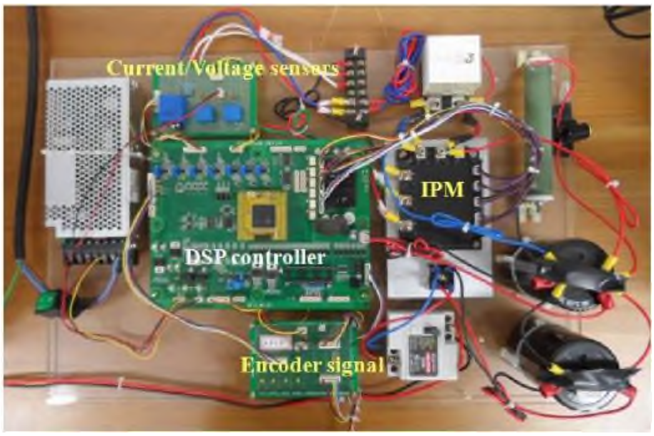


Figure 3. Configuration of the DSP Controller

Figure 4 shows the overall configuration of the experimental system consisting of DSP controller, LIM, and PWM inverter.

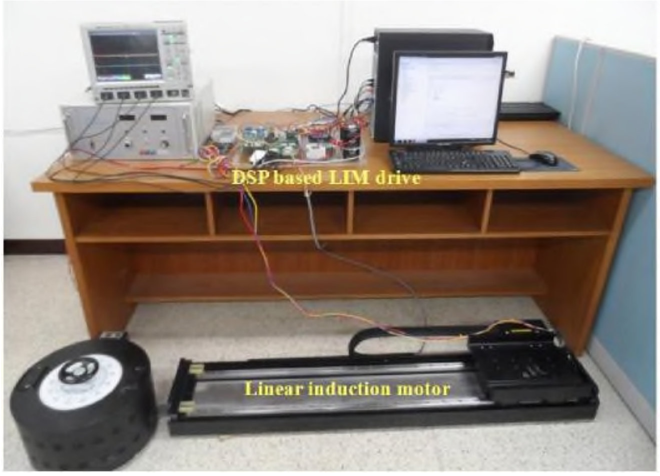


Figure 4. Configuration of the Experimental System

5. Simulation and Experimental Results

In this section, the comparative simulation and experimental results are presented to verify the robust control performance of the LIM for the APS. The whole system consists of a LIM, a current controller, a field-oriented controller and a PWM inverter. For a current control algorithm, the synchronous PI decoupling scheme is employed. The block diagram of the integral SMC for the LIM is shown in Figure 5.

To evaluate the robustness through comparative simulations, five test conditions are chosen as follows:

Test condition 1:

Test condition 2:

Test condition 3:

Test condition 4:

Test condition 5: .

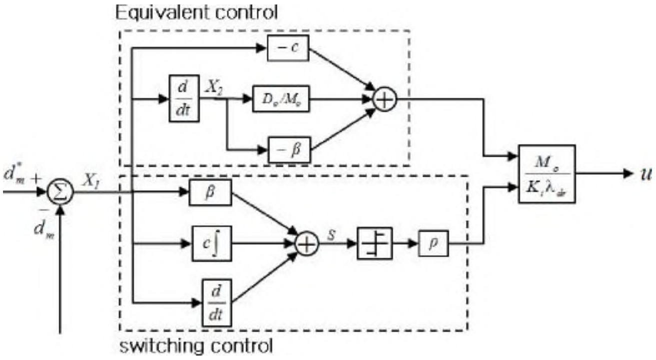


Figure 5. Block Diagram of the Integral SMC

Figure 6 shows the responses of the PI position controller under five test conditions when the position reference is 1[m]. Although this control gives a relatively good performance under the nominal mechanical parameter values such as in the test condition 1, its responses are not satisfactory under the parameter variations. Under the mass variation, the transient responses tend to be sluggish. On the other hand, it shows steady-state positions errors under the existence of external disturbance.

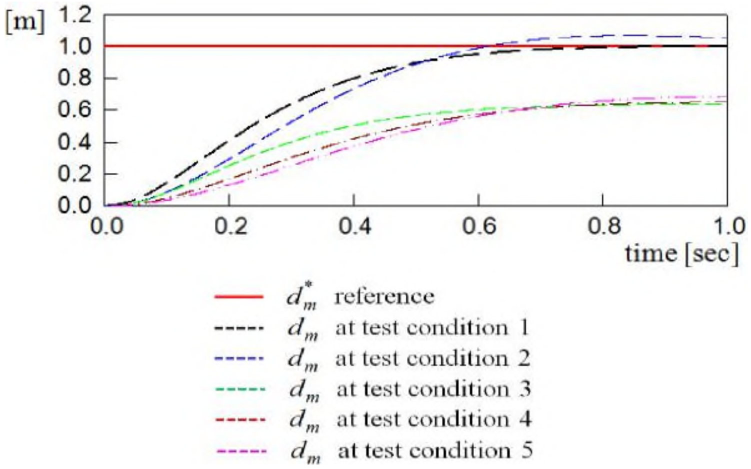


Figure 6. Control Performance of the PI Control Under Five Test Conditions

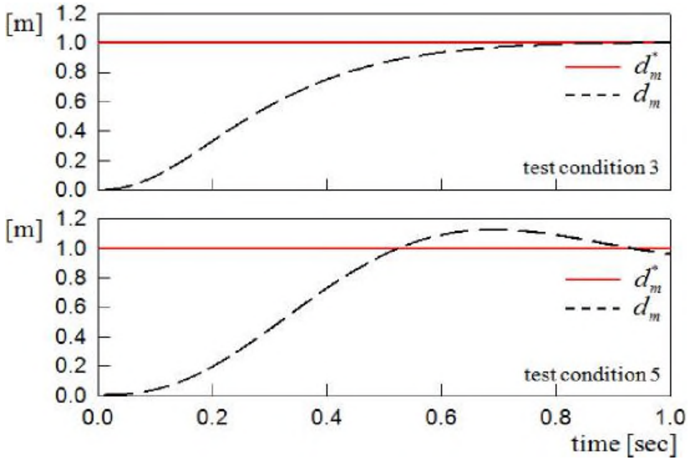


Figure 7. Control Performance of the PI Control with the Force Observer Under Test Conditions 3 and 5

Figure 7 shows the control performance when the disturbance is compensated with the force observer under the test conditions 3 and 5. As shown in these figures, the force observer effectively works under the constant disturbance. However, the control performance is not satisfactory under the mass mismatch because the compensation performance is degraded with the time-varying disturbance caused by the mass variation.

These degraded control performance can be effectively improved by using the integral SMC approach. Figure 8 shows the responses of the integral SMC-based position controller under the same test conditions. The gains for the integral SMC are chosen as □=7 and c=8. As compared with Figure 6, the position responses of this control yield almost similar waveforms under five test conditions irrespective of the mechanical parameter variation. This comes from the fact that the state error can be always maintained on the sliding surface without reaching mode according to initial conditions.

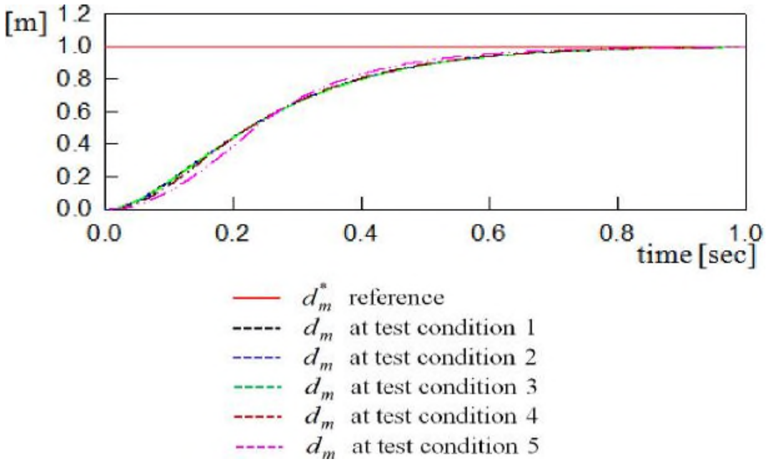
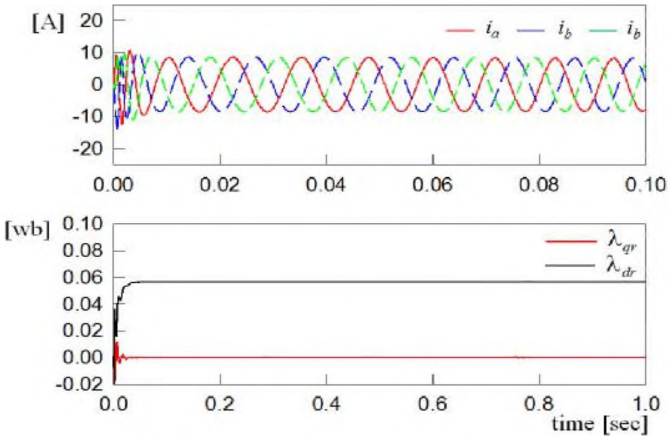
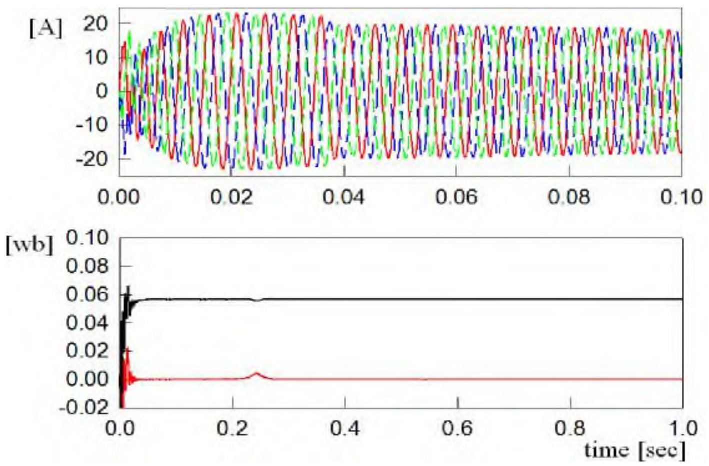


Figure 8. Control Performance of Integral SMC-Based Position Control Under Five Test Conditions

Figure 9 shows the phase current and flux waveforms for the PI control and integral SMC under the test condition 5, respectively.

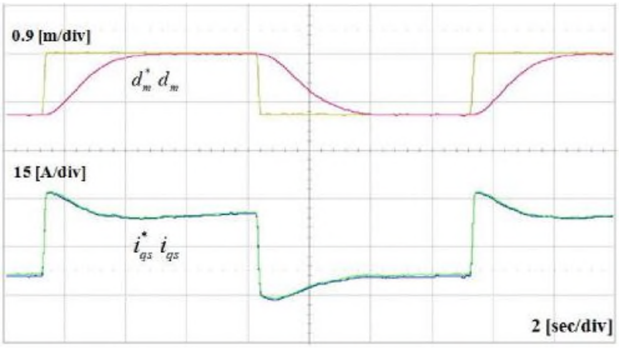


(a) PI control

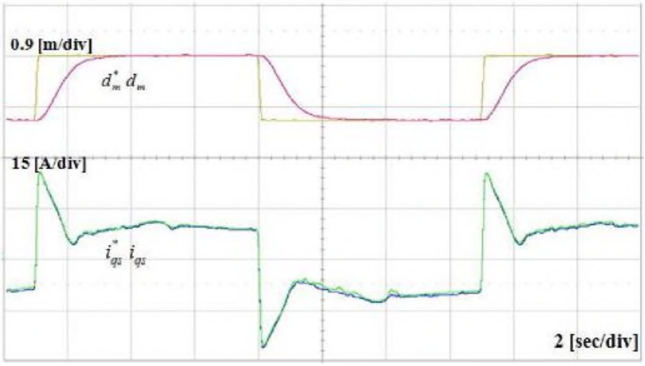


(b) Integral SMC

Figure 9. Phase Current and Flux Waveforms Under the Test Condition 5



(a) PI controller

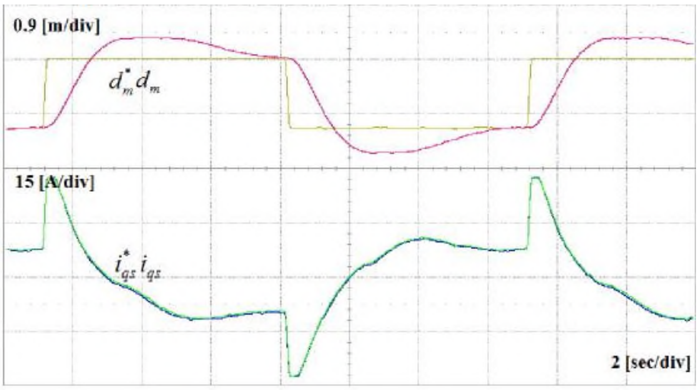


(b) Integral SMC

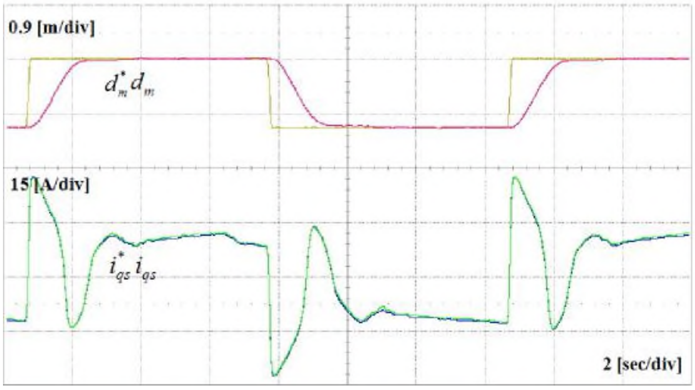
Figure 10. Control Performance of the PI Control and the Integral SMC Under the Nominal Test Condition

Figure 10 shows the experimental results of the PI position controller and the integral SMC under the nominal mechanical parameter values. The position references are given as step waveforms using the magnitude of 0.9[m] and 0.3[m]. It is observed in this figure that two controllers yield similar position responses at the nominal condition.

Figure 11 shows the experimental results of the PI position controller and the integral SMC under the mass variation. The other operating conditions including the gains and position references are selected as the same with Figure 10. It is clearly shown that the response of the PI controller is not satisfactory under the mass variation with too long transient period. On the other hand, the integral SMC shows good transient and steady-state responses, which is quite similar to the response under the nominal condition.



(a) PI controller

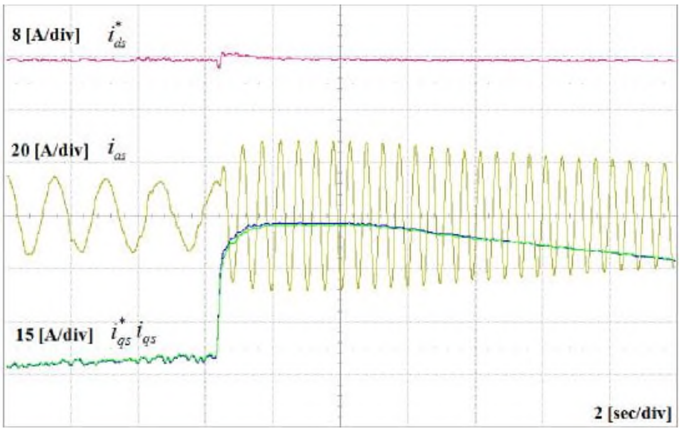


(a) Integral SMC

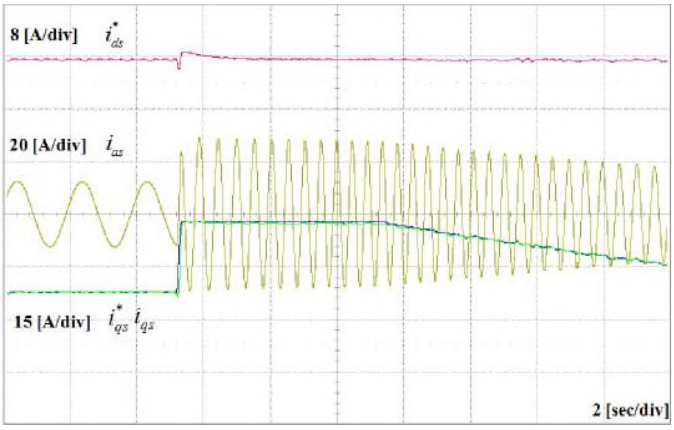
Figure 11. Control Performance of the PI Control and the Integral SMC Under the Mass Variation of M=1.5Mo

Figure 12 shows the *d*-axis, *q*-axis, and phase current responses for the PI controller and the integral SMC under the same operating conditions with Figure 11.

From these results, it is confirmed that the proposed scheme based on the integral SMC can be an effective way of implementing an APS since it possesses more robust position responses with high dynamic and high accuracy.



(a) PI controller



(b) Integral SMC

Figure 12. Control Performance of the PI Control and the Integral SMC Under the Mass Variation of M=1.5Mo

6. Conclusions

To operate APS equipments with high precision and high dynamics, a robust position controller of a LIM using an integral SMC scheme has been presented. To reduce the influences of uncertainty such as the disturbance thrust and the mismatch in mass or friction coefficient, the integral SMC-based position controller is employed. A Simulink library model for the LIM is developed using the LIM dynamic model to evaluate the control performance through the comparative simulations. For experimental verification, the whole control system is implemented using DSP TMS320F28335. The comparative simulations and experiments have been done under different test conditions. As a result, the proposed scheme can effectively compensate the parameter uncertainty such as the disturbance force as well as the mass variation in movable ejector. Thus, the proposed scheme can be a good candidate for APS.

Acknowledgements

This work was supported by the GRRC programme of Gyeonggi province. [(GRRC HANKYONG 2012-B02), Development of Automatic Picking System with Traveling Dispensers and Automatic Classification and Defect Detection System with Machine Vision Technology]

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