PROCEEDINGS

Proceedings will be published in time for the symposium and a copy with CD will be given to each registrant at the registration desk.

TECHNICAL TOUR

A technical tour is under planning. Latest information will be provided at the LDIA 2009 Home Page. (http://www.LDIA2009.kr)

SPONSORSHIP

Sponsored by

Seoul National University

In cooperation with

Korea Elctrical Engineering & Science Research Institute (KESRI)

Korea Institute of Information & Telecommunication Facilites Engineering (ITFE)

The Korean Institute of Electrical Engineers (KIEE)

The Institute of Electrical Engineers of Japan(IEEJ)

ORGANIZATION

International Steering Committee

Chairperson : D. Ebihara Musashi (Institute of Tech. Japan, Japan)

Organizing Committee

Chairperson : H. K. Jung (Seoul Nat'l Univ., Korea)

Program Committee

Chairperson : J.P. Hong (Hanyang Univ., Korea)

LDIA2009 SECRETARIAT

Prof. S. Y. Jung

Department of Electrical Engineering, Dong-A University

840, Hadan2-dong, Saha-gu, Busan, Korea, 604-714

Phone : +82-2-880-7262 / Facsimile : +82-2-878-1452

E-mail: ldia2009@elecmech.snu.ac.kr

http://www.LDIA2009.kr

KOREA TOURISM ORGANIZATION
www.tour2korea.com

http://www.LDIA2009.kr

The First Announcement and Call for Papers

The Seventh International Symposium on

LDIA 2009

Linear Drives for Industry Applications

September 20-23, 2009

Hyatt Regency Incheon, Korea

OBJECTIVES

The Seventh International Symposium on Linear Drives for Industry Applications (LDIA2009) will provide a forum for the discussion of present research and development activities and future prospects related to the linear drives for industry applications. Although linear drive systems have spread to applications in industry, there still remain many issues to be solved. This symposium will contribute to find these solutions and the further development of linear drive technology.

VENUE

The Symposium will be held at the Hyatt Regency Incheon, Korea. Strategically located at the International Business Centre, Hyatt Regency Incheon is set to take its place as the city's premier venue for corporate meetings and conferences.

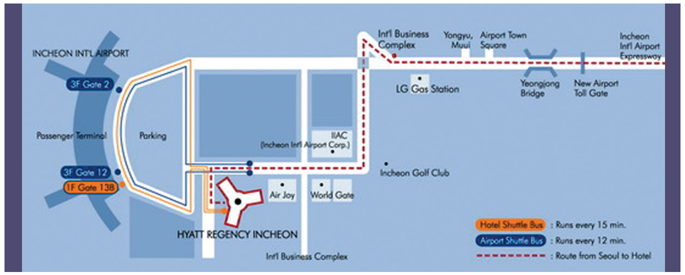
Cleverly combining its contemporary design and state-of-the-art technology with culinary expertise and classic standards of service excellence, it bring to the city of Incheon world-class luxury, innovative dining and entertainment. Only minutes from the new incheon International Airport, Hyatt Regency Incheon is a distinctive new landmark and a welcoming residence as a home away from home to visitors of this gateway city.

About Incheon

Incheon was promoted to a city under direct government supervision on July 1, 1981. On January 1,1989, Gyeyang-myeon of Gimpo-gun and other districts of Gyeonggi-do Province, including Yeongjong-myeon and Yongyu-myeon of Ongjin-gun were merged into the city. A gateway to Northeast Asia with both international port and international airport in its hand, Incheon is located in the mid-west Korea peninsula abutting the Yellow Sea. A city located 28km from the nation's capital, Seoul, lies at 126° 37'' of east longitude and 37° 28′ of north latitude. San Francisco, Washington, Madrid, and Teheran are found on the same latitude.

TRANSPORTATION

You can find Hotel shuttle, Airport shuttle and KAL limousine information in the Home Page of LDIA 2009.



ACCOMMODATION

The Organizing Committee will provide Information about other hotels within twenty minutes trip by bus from the conference site. Further detail information will be provided through the LDIA2009 Home Page.

PROGRAM

Sept. 20 Registration, Welcome Party
Sept. 21 Opening Ceremony, Plenary Lectures, Technical Sessions, Banquet
Sept. 22 Technical Sessions, Closing Remarks
Sept. 23 Technical Tour

TOPICS

00 Trend and new development of linear drives (survey)

10 Electromagnetic linear motors and actuators
- 11 linear motors
- 12 linear actuators
- 13 nano-, micro-actuators
- 14 multi-dimensional linear drives

20 Non-electromagnetic linear motors and actuators
- 21 linear motors
- 22 linear actuators
- 23 nano-, micro-actuators
- 24 multi-dimensional linear drives
- 25 bio-actuators
- 26 Piezo electric Actuators

30 Control technologies for linear drives
- 31 linear drive and motor control
- 32 control theory
- 33 applications of new control theory
- 34 modeling and identification

40 Levitation technologies
- 41 magnetic levitation for linear drives
- 42 magnetic suspension for motor revolution
- 43 electric field levitation
- 44 control strategies
- 45 novel levitation control scheme

50 Subsystem for linear drives
- 51 bearings
- 52 power sources and power conversion
- 53 sensors and measurement systems

TOPICS

60 Applications of linear drives and levitation technologies
- 61 transportations
- 62 factory automation and machine tools
- 63 office automation
- 64 robotics
- 65 home and medical applications

70 Analysis of electromagnetic field and force field
- 71 numerical analysis
- 72 analysis of coupled system
- 73 visualization
- 74 dynamics

80 Materials
- 81 permanent magnet
- 82 superconductor
- 83 piezo device
- 84 magnetic materials
- 85 special design of force elements

90 Other related topics and new technologies

CONTRIBUTIONS

Prospective authors should submit a single page abstract, in English, on one side of A4 or letter-size paper in Word or PDF electronic file, by January 31, 2009. This abstract should be headed by the title of the paper, names and affiliations of authors, mailing address, phone and facsimile numbers, e-mail address, and the topic number(s), followed by the summary of the paper's contents, clearly indicating the aim and the results of the work. Please refer to latest information in the LDIA2009 Home Page.

DEADLINES

Receipt of abstracts : **January 31, 2009**
Notification of acceptance : **March 31, 2009**
Receipt of full papers : **June 30, 2009**

LANGUAGE

The official language of the Symposium is English, which will be used for all printed materials, presentations and discussions.

Linear Drives for Industry Applications

Active magnetic guidance for material handling systems based on linear motors

Phong C. KHONG, Roberto LEIDHOLD and Peter MUTSCHLER
Department of Power Electronics and Control of Drives, Technische Universität Darmstadt, Germany
e-mail: phong@srt.tu-darmstadt.de

Topics: 31, 11

1. Introduction

Linear drives provide new solutions for material transportation and processing in the manufacturing industry. Instances of application can be found for stretching of plastic films [1] or in material handling [2]-[4].

For these applications, the linear motor is typically with stationary long primary and a short moving secondary [4]. As the secondary part is passive, no electrical energy transmission is required between the moving and stationary part. The best suited motor type for the mentioned application is the synchronous one with permanent magnets, because of its higher efficiency, compactness and because it allows a wider air-gap.

In the usual approach, the linear motor is only used for thrust force production. The guidance is usually implemented by a mechanical assembly. Such a mechanical assembly can be complex and source of high friction. It becomes even more complex when the track is non-straight as e.g. in curvilinear conveyor systems.

Several proposals can be found in the literature to substitute the mechanical guidance, partially or totally, by magnetic guidance. Magnetic levitation will be considered here as the guidance for vertical displacement and pitch. Magnetic bearings and bearing-less motors are the rotative counterparts of magnetic guidance, and several methods derive from them.

By using electro-dynamic levitation or null-flux coils [5], passive magnetic guidance can be provided for one or more degrees of freedom. The drawback is the dependence on the longitudinal speed i.e. it does not provide guidance at standstill. The superconducting magnetic bearing [6] is a passive guidance method that works even in standstill, requiring however a cryogenic system.

Different methods for active magnetic guidance can be found proposed, among the others, in [7]-[10]. These methods rely on using separate windings for the guidance and propulsion. These windings are located in the mover, requiring therefore an energy transmission system to the mover. In [11], the windings used for propulsion, i.e. motor's primary, are also used for guidance (levitation). As the primary is in the mover, here again an energy transmission system is required. The proposal of [12] is a complete magnetic guiding system for a long primary linear motor. The air-cored primary is placed in the guideway and is used for propulsion as well as for the guidance. In this case, the mover does not need a power supply besides for the position sensors. The magnitude, angle and zero-sequence of the currents supplied to each primary-side are the manipulated variables to control the longitudinal movement and the guidance.

In the present paper, an active guiding system is presented for PM-synchronous linear motors with long and double-sided primary. The lateral displacement, the yaw angle and the vehicle position are controlled while a simple wheel-rail system fixes the vertical displacement. This combination of magnetic and mechanical guidance offers a good tradeoff among the complexity of the control, actuators and mechanics, when considering industrial applications. Each side of the primary is supplied by its own inverter, allowing the necessary degree of freedom to control the lateral position and yaw angle in addition to the thrust. With this arrangement, the mover can be kept passive avoiding any energy transmission system to it (besides for the sensors). Unlike [12], here a standard three-phase iron-cored primary section is used. In addition, the direct and quadrature current components in a field-oriented reference frames are the manipulated variables instead of the magnitude and angle.

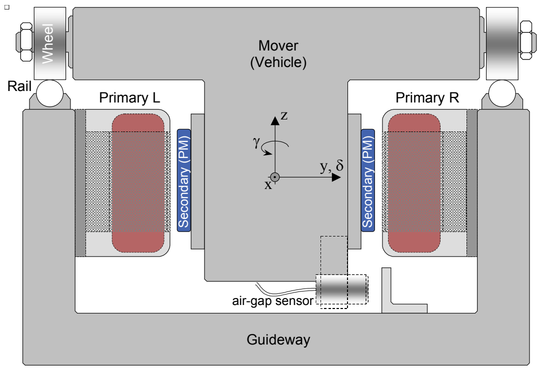


Figure 1: Cross section of the long-primary linear motor.

2. Model of the linear motor

The machine considered for the proposed guidance system is a long-primary (guideway) with a short-mover (vehicle) linear motor. A cross section of the system is shown in Fig. 1. The vehicle has two secondary sections mounted opposite each other in the lower part of the vehicle. Each secondary section has a permanent magnet (PM) array fastened on a back iron plate. The iron-cored primary sections are installed along both sides of the guideway. Each primary side section is fed separately to generate lateral and propulsive force on the correlative secondary section. With that structure, the movement in y-axis can be controlled by the differential lateral forces, the rotation and x position of the mover are controlled respectively by the difference and total of propulsive forces. The movement in the z-axis is constrained by the rail-wheel system. The lateral displacement i.e. in the y-axis, is named as δ , and the yaw angle γ .

The forces acting on the mover are function of the left and right side d-axis currents (i_{dL}, i_{dR}), q-axis currents (i_{qL}, i_{qR}), lateral position δ and yaw γ. These forces can be demonstrated:

$$F_x = i_x K_x + F_{xp}(\delta, \gamma, i_x, i_\delta, i_\gamma) \quad (1)$$

$$F_\delta = i_\delta K_\delta + F_{\delta p}(\delta, \gamma, i_x, i_\delta, i_\gamma) \quad (2)$$

$$T = i_\gamma K_\gamma + T_p(\delta, \gamma, i_x, i_\delta, i_\gamma) \quad (3)$$

where K_x, K_δ and K_γ are constants of the motor; F_{xp}, $F_{\delta p}$ and T_p are the force and torque, respectively, resulting from the attraction between the magnets and the primary iron; i_x, i_δ and i_γ are the propulsion, lateral force and yaw torque producing currents, respectively, related with the primary currents as follows:

$$\begin{cases} i_{qL} = i_x + i_\gamma, \qquad i_{qR} = i_x - i_\gamma & (4) \\ i_{dL} = -\dfrac{i_\delta}{2}, \qquad i_{dR} = \dfrac{i_\delta}{2} & (5) \end{cases}$$

The forces F_{xp}, $F_{\delta p}$ and T_p are dependent on the position, dq current (i_d, i_q) of left and right primaries, and can be considered as perturbations. In other words, the control algorithm can work without compensating $F_{\delta p}$, F_{xp} and T_p, however at the cost of a poorer performance. To obtain a higher control quality, they will be compensated in the control algorithm.

The motion equations are:

$$\frac{dv}{dt} = \frac{F_x}{M}, \quad \frac{d\varepsilon}{dt} = \frac{F_\delta}{M}, \quad \frac{d\omega}{dt} = \frac{T}{J} \quad (6)$$

$$\frac{dx}{dt} = v, \quad \frac{d\delta}{dt} = \varepsilon, \quad \frac{d\gamma}{dt} = \omega \quad (7)$$

With M and J being the mass and moment of inertia of the mover, respectively.

3. Proposed control method

Based on the approximated model (1)-(7), considering all values $F_{\delta p}$, F_{xp} and T_p as the perturbations, and a current controlled inverter, it is proposed to use a standard cascaded controller for each degree of freedom:

$$i_x^* = k_{pv}(v^* - v) + \frac{k_{pv}}{T_i}\int_0^t (v^* - v)\,dt \quad (8)$$

$$i_\delta^* = k_{p\varepsilon}(\varepsilon^* - \varepsilon) + \frac{k_{p\varepsilon}}{T_i}\int_0^t (\varepsilon^* - \varepsilon)\,dt \quad (9)$$

$$i_\gamma^* = k_{p\omega}(\omega^* - \omega) + \frac{k_{p\omega}}{T_i}\int_0^t (\omega^* - \omega)dt \quad (10)$$

$$v^* = k_{px}(x^* - x) \quad (11)$$

$$\varepsilon^* = k_{p\delta}(\delta^* - \delta) \quad (12)$$

$$\omega^* = k_{p\gamma}(\gamma^* - \gamma) \quad (13)$$

The parameters of the controller (k_{pv}, $k_{p\varepsilon}$, $k_{p\omega}$, T_i, k_{px}, $k_{p\delta}$ and $k_{p\gamma}$) are determined by the symmetrical optimum criteria using the approximated model. With these parameters, the stability of the equilibrium points was proved in a wide set of positions, using the complete model, by numerical analysis.

The reference values for lateral position δ^* and yaw angle γ^* are set to zero, while the reference for the longitudinal position x^* is determined by the task assigned to the system.

In order to compute the parameters of (1)-(3) for controller designing, a sinusoidal winding distribution is assumed and is modeled by a thin current layer. In the same way, the PMs are assumed producing a sinusoidal flux distribution along the mover's length. In the case that the air-gap is constant along the mover's length, the force analysis yields closed equations [13]. However, in the case that a yaw angle is considered, the air-gap is not constant along the mover's length and a closed expression of the forces are not possible anymore. In this case, the forces should be computed numerically for a given motor.

With respect to improve the control quality, a compensating control method was implemented to reduce the perturbation of lateral force $F_{\delta p}$. Although, as mentioned above, the force equations cannot be expressed in closed form when the yaw angle is considered. So, here for the practical calculation, the effect of yaw angle is neglected. The equation (2), after linearization, can be simply rewritten as:

$$F_\delta = i_\delta K_\delta + F_{\delta p}(\delta, i_x, i_\delta, i_\gamma) \quad (14)$$

$$\begin{aligned} F_{\delta p}(\delta, i_x, i_\delta, i_\gamma) &= K_1\delta - K_2\left(i_L i_{dL} - i_R i_{dR}\right) \\ &- K_3\left(i_L i_{dL} + i_R i_{dR}\right)\delta - K_4\left(i_{dL} + i_{dR}\right)\delta \end{aligned} \quad (15)$$

Where K_1, K_2, K_3, K_4 are constants of the motor; i_L, i_R are the current vector amplitudes of left and right stator.

$$i_L = \sqrt{i_{dL}^2 + i_{qL}^2} \quad (16)$$

$$i_R = \sqrt{i_{dR}^2 + i_{qR}^2} \quad (17)$$

The proposed reference current for delta-control becomes

$$i_{\delta C}^* = i_\delta^* - F_{\delta p}(\delta, i_x, i_\delta, i_\gamma) / K_\delta \quad (18)$$

The control block diagram is show on Fig.6.

4. Experimental setup and results

In order to test the proposed system, a prototype based on the diagram of Fig. 1 was implemented. The prototype was built on aluminum profiles and standard commercial stators and magnets. In Fig. 2 a picture of the prototype is shown. In Table 1 the most important parameters are given.

Table 1: Main parameters of the linear motor

Primary length	542 mm
Secondary length	144 mm
Lateral displacement range	3 mm
Pole pitch	36 mm
Rated current	2.9 A rms
Maximal current	21.3 A rms
Rated thrust force	210 N
Mass of the mover	5.7 Kg
Moment of inertia of the mover	0.038 Kg.m2

Each primary side is supplied with its own inverter, with a 5 kHz switching frequency. All inverters are controlled by one PC-based controller using the RTAI-Linux real time operating system. The control algorithm operates at a sampling frequency of 10 kHz. The space-vector PWM generation and the AD conversions are performed in self-developed interface boards.

The longitudinal position is measured by a linear encoder with magnetic scale and magneto resistive sensor. The resolution of the encoder is 5 µm. Two analog proximity sensors are placed at the ends of the mover. The lateral position is obtained from the average of both sensors, and the yaw angle from the difference. These sensors have a bandwidth of 10 kHz.

Experimental results were obtained with the described experimental setup. A test was performed to check the

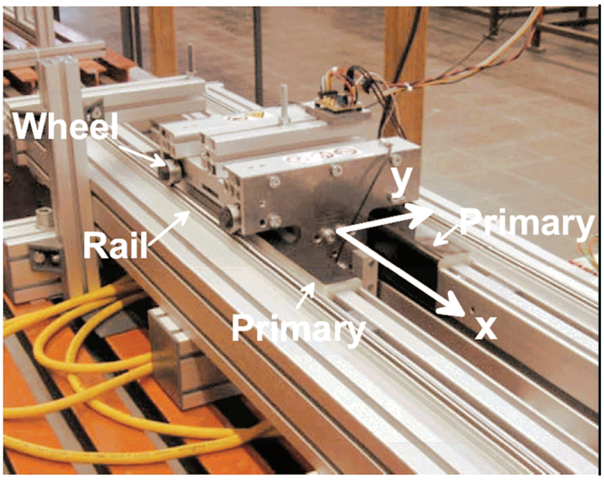


Figure 2: Prototype of the linear motor with magnetic guidance

control ability of the proposed method on the prototype system. The test is implemented to control the three-degree of freedom simultaneously. The system is started from a rest position with the highest absolute value of delta ($-\delta_{max}$). At $t = 0.1s$, the references δ^*, γ^* are set to zero (mover centered and parallel to the guideway) and x^* is set to 100. The measured lateral position, yaw angle and longitudinal position are shown in Fig. 3 as a function of time. At $t = 0.4s$, the reference for the longitudinal position is set to $x^* = 300\,mm$. At t = 0.9 s, the reference γ^* is established to a new value of 0.5 mrad.

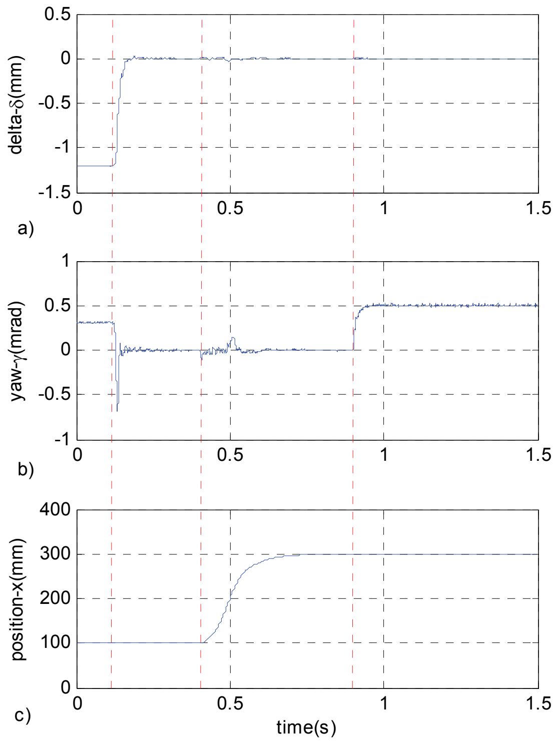


Figure 3: Startup and longitudinal movement (experimental); lateral position, yaw angle and longitudinal position are shown

The current i_d, used for delta control, and the current i_q, used for gamma and x control, are components of the same current vector. The magnitude of the current vector must be limited by limiting each of its components. On other hand, the attractive force between the primary iron-core and the PM (lateral force) is very high. Therefore, in the control algorithm, a higher priority is given to the current component for delta control (i_d) while limiting the other component (i_q). That is why at t = 0.1 s delta is controlled well and gamma oscillates in short time. However, at t = 0.9 s when the vehicle is in the middle of the guideway, the lateral force is balanced between left and right side. Consequently, i_d is small at that time and a step in gamma reference γ^* is responded with higher quality. During the movement of the vehicle from 100mm to 200mm, there is some disturb to gamma and delta. The ability to startup from the rest position shows that the controller is able to compensate all couplings between delta and gamma control loops.

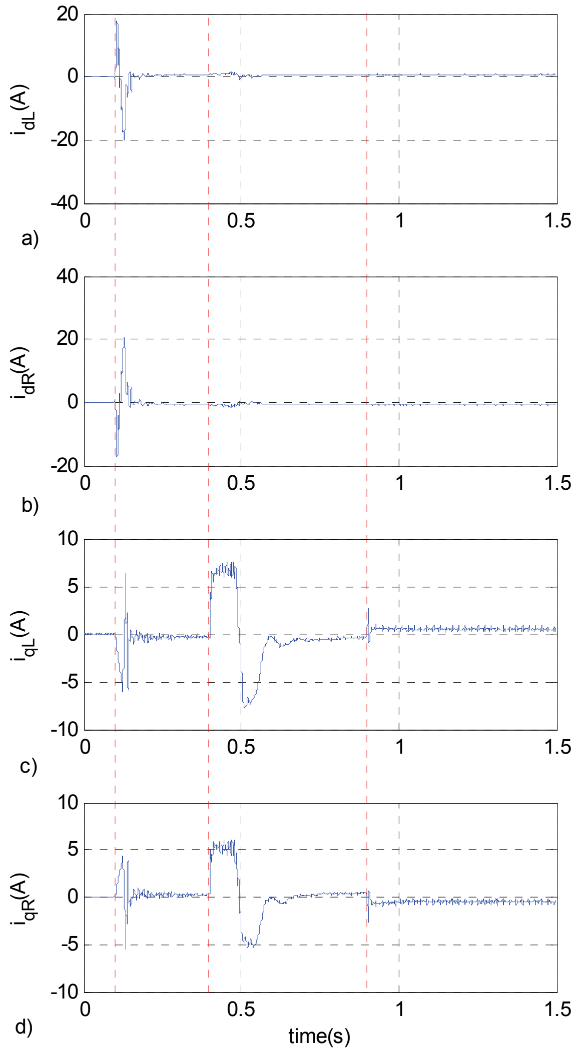


Figure 4: Field oriented current i_d, i_q of left and right side.

The resulting measurements of currents i_d and i_q are presented in Fig. 4 as the function of time. In Fig 4.a and 4.b, i_{dL} and i_{dR} are symmetrical because of (5). They are very high when the delta position of the vehicle is controlled from rest position to zero. When the vehicle is in the middle of the guide way, the required i_d is much smaller (almost zero). The currents i_{qL} and i_{qR}, shown in Fig. 4.c and d, generate the thrust force and rotating moment for the vehicle. So, when the vehicle is moving or rotating, the total and difference of i_{qL} and i_{qR} change correlatively.

In Fig. 5 the corresponding currents for lateral force (i_δ), yaw torque (i_γ) and propulsion force (i_x) are shown. They relate with i_d and i_q as mentioned in (4) and (5).

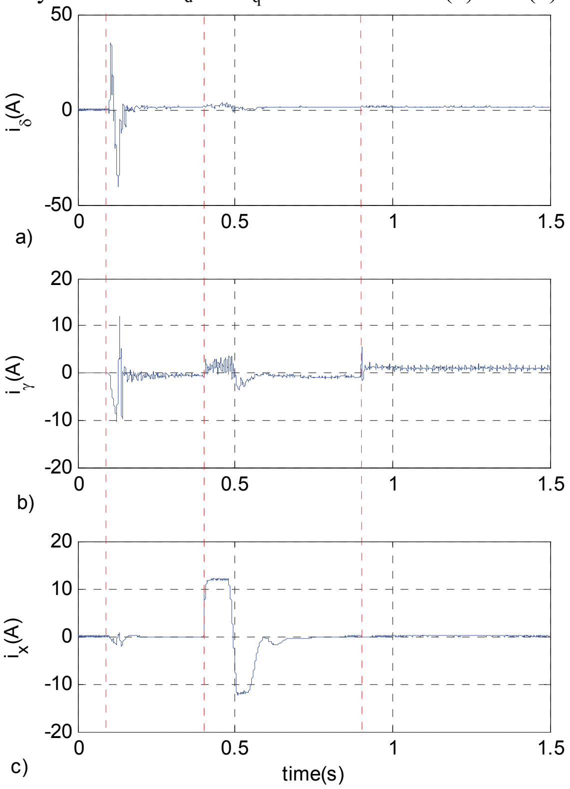


Figure 5: The propulsion, lateral force and yaw torque producing currents

5. Conclusions

An active magnetic guidance for PM-synchronous linear motors with long primary was presented. Applications like in-plant transport and handling systems would specially profit from it. The use of active magnetic guidance for the lateral displacement and yaw angle, while keeping a mechanical guidance for the vertical displacement, simplifies the mechanical assembly significantly without higher complexity in electromagnetic actuators or control. The experimental results show the viability of the proposed system and its control algorithm.

Acknowledgement

This work is funded by the Deutsche Forschungs-gemeinschaft DFG, Grant MU 1109/18-1 *"Magnetisch geführter Linearantrieb"*

References

[1] B. Sieber, J. Breil, *"New developments for a linear motor system with multiple carriers,"* in Int. LDIA2003 Symp., 2003, pp. 21-24.

[2] C. Bosshard, *"MagneTrak(c) Paradigmenwechsel im Materialhandling,"* in 13. Deutscher Materialfluss-Kongress Innovative Techniken für die Logistik. vol. 1815 Garching, Germany, 2004, pp. 189-200.

[3] G. Stöppler, *"Segmentierte Langstator-Linearmotoren für die Schnellpositionierung von Werkstückträgern in längsverketteten Montagelinien,"* in SPS/IPC/DRIVES, Nuremberg, Gemany, 2008.

[4] P. Mutschler, *"Comparison of topologies for linear drives in industrial material handling and processing applications,"* in ICPE '07., 2007, pp. 1027-1032.

[5] J. de Boeij, M. Steinbuch, and H. M. Gutierrez, *"Modeling the electromechanical interactions in a -flux electrodynamic maglev system,"* IEEE Trans. on Magnetics, vol. 41, pp. 466-470, 2005.

[6] S.O. Siems, W.-R. Canders, *"Experimental investigation of linear and rotatory HTSC bearings for industrial applications,"* Int. Journal of Applied Electromagnetics and Mechanics, vol. 19, pp. 199-202, 2004.

[7] K. Ben-Yahia, G. Henneberger, *"Linear magnetic bearing for high speed machine tools,"* in PCIM 99 Nürnberg, 1999.

[8] W. Evers, G. Henneberger, *"A New Linear Drive for a Magnetic Levitation Transport System,"* in EPE 99 Lausanne, 1999.

[9] A. D'Arrigo, A. Rufer, *"Design of an integrated electromagnetic levitation and guidance system for SwissMetro,"* in EPE 99 Lausanne, 1999.

[10] I. da Silva and O. Horikawa, *"Experimental development of a one-degree-of-freedom controlled magnetic linear bearing,"* IEEE Trans. on Magnetics, vol. 41, pp. 4257-4260, 2005.

[11] K. Yoshida, T. Yoshida, K. Noda, *"Combined-Levitation-and-Propulsion Control of SLIM Maglev Vehicle on Flexible Guideway,"* in EPE 2003 Toulouse, 2003.

[12] K. Yoshida, T. Yoshida, S. Manabe, and T. Yorishige, *"Control of New PM LSM Maglev Vehicle Based on Analysis of Pitching Torque and Propulsion Force,"* in IEEE-ISIE 2007, 2007, pp. 1125-1130.

[13] I. Boldea, S.A. Nasar, *Linear electric actuators and generators*. Cambridge; New York: Cambridge University Press, 1997.

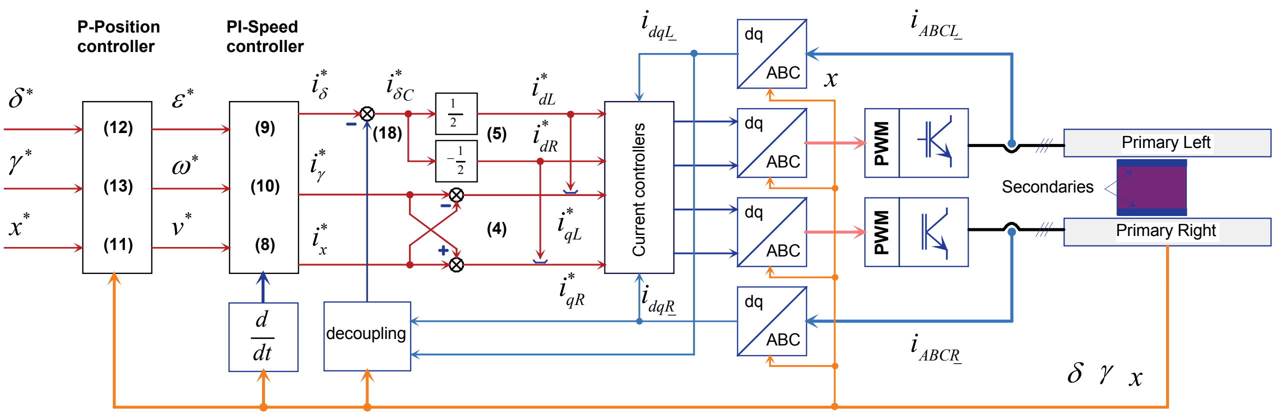


Figure 6: Control block diagram