Comparison between resonant and PI controllers for thrust control of a permanent magnet linear synchronous motor

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ABSTRACT: This paper proposes to compare two control strategies for thrust control with back-electromotive harmonics compensation of a permanent magnet linear synchronous motor (PMLSM). The first method uses multiple synchronous reference frames with PI controllers and the second method uses diphase reference frames with resonant controllers. Then, control structures and controllers designs are described for both methods. Simulations and experimental results are compared on a test bench equipped with a PMLSM.

1 INTRODUCTION

1.1 Context

Linear motors have been widely used in various industrial fields, with universally recognized advantages (Gieras 2000). The regulation of the load currents in linear motors is an important issue for high-efficiency applications, for reduction of vibrations in high-precision systems such as machine-tools applications, *etc.* (Groß 2001). The electromagnetic thrust generated by a PMLSM is directly connected to the design of the winding distribution. For example with a trapezoidal distribution, the thrust has harmonics 5 and 7 times or more superior to the load currents fundamental (Remy 2005).

Nowadays, improvement of the thrust control of a permanent magnet linear synchronous motor (PMLSM) is based on the compensation of harmonics in the load currents. For a surface-mounted permanent magnet synchronous motor with non-sinusoidal back-electromotive forces, it has been proved that injection of the appropriate current harmonics leads to a reduction of the thrust ripple (Hung 1992, Chapman 1999b). Classically, thrust closed-loop control can be developed using two techniques in order to focus on current harmonics:

- The multiple synchronous reference frames (so-called rotor reference frames or rotating reference frames or Park's reference frames).
- The diphase reference frames (so-called stator reference frames).

The main difference between these two techniques is the controllable quantities, which are constant in the multiple synchronous reference frames and sinusoidal in the diphase reference frames.

1.2 The multiple synchronous reference frames

Given the synchronous behavior of the actuator, all the quantities (voltage, current, flux, *etc.*) can be referenced in synchronous reference frames. For the control of a synchronous motor, the main advantage of synchronous reference frames is that at a rated speed, all the quantities are aligned and constant in the *direct-axis* and in the *quadrature-axis* (Fitzgerald 2003). The number of frames is directly established using the number of harmonics of the quantities. The classical control structure using multiple synchronous reference frames is represented in Figure 1:

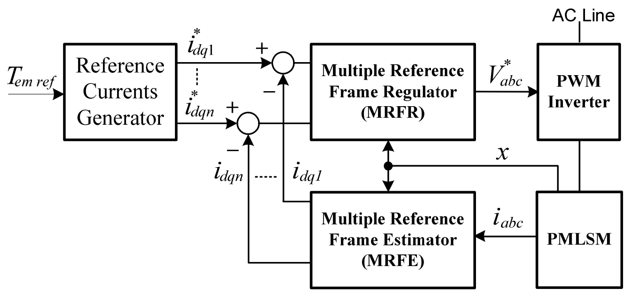

Figure 1: System diagram of thrust control with multiple reference frames.

This control structure is composed of a reference current generator, which decomposes the thrust reference in two reference currents by frame. Then, the reference currents are compared to the estimated currents given by multiple reference frames estimator (MRFE). And finally, the error between the references and the measurements are reduced by a multiple reference frames regulator (MRFR). The MRFE and the MRFR can work with different techniques:

- The MRFE can use a frequency splitter and then *n* Park's transforms are applied to obtain *n* frames. The MRFR can use two PI controllers on each *n* frame and then applies Park's Inverse transforms.
- The MRFE can use *n* Park's transforms and then applies a low-pass filter on each of the *n* frames. The MRFR can use two PI controllers on each of the *n* frames (Park 2000).
- The MRFE can use *n* Park's transforms combine with a convergence algorithm on each of the *n* frames. The MRFR can use an algorithm to make converge the estimated currents with there reference on each of the *n* frames (Chapman 1999a).

The multiple synchronous reference frames with PI controllers is a good solution to eliminate the persistent phase error in a control loop, even if the control signal is non-sinusoidal. The main drawbacks of this approach are the computational effort for the coordinate transforms: two transforms are required for each harmonic component; and the low response time of the reference frame estimator.

The transform of multiple synchronous reference frames is defined as:

$$K^x = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(x\theta_e) & \cos\left(x(\theta_e - \frac{2\pi}{3})\right) & \cos\left(x(\theta_e + \frac{2\pi}{3})\right) \\ -\sin(x\theta_e) & -\sin\left(x(\theta_e - \frac{2\pi}{3})\right) & -\sin\left(x(\theta_e + \frac{2\pi}{3})\right) \end{bmatrix} \quad (1)$$

$$K^{x^{-1}} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(x\theta_e) & -\sin(x\theta_e) \\ \cos\left(x\left(\theta_e - \frac{2\pi}{3}\right)\right) & -\sin\left(x\left(\theta_e - \frac{2\pi}{3}\right)\right) \\ \cos\left(x\left(\theta_e + \frac{2\pi}{3}\right)\right) & -\sin\left(x\left(\theta_e + \frac{2\pi}{3}\right)\right) \end{bmatrix} \quad (2)$$

Wherein $i^x_{dq} = K^x * i_{abc}$, and $i_{abc} = \Sigma(K^x)^{-1} * i^x_{dq}$.

Classically, the current value can be controlled using a hyteresis controller or a PI controller.

1.3 The diphase reference frame

The diphase reference frame (Concordia's reference frame) uses the Concordia transform:

$$T_3 = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}, \ \textit{and} \ T_3^{-1} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (3)$$

Wherein $i_{\alpha\beta} = T_3 * i_{abc}$, and $i_{abc} = T_3^{-1} * i_{\alpha\beta}$.

As the currents in a diphase reference frame are sinusoidal, for the regulator we can only find hysteresis controllers or resonant controllers (Guillaud 1999).

The resonant controller solution lies in associating several resonant elements in series in one single controller without using too-complex algorithms. This controller allows us to control both the fundamental and the harmonic components (several harmonic frequency controllers can operate with the fundamental frequency controller in parallel).

2 THE MULTIPLE SYNCHRONOUS REFERENCE FRAMES TUNING

2.1 Control Structure

The control structure of the multiple synchronous reference frames is represented in Figure 2:

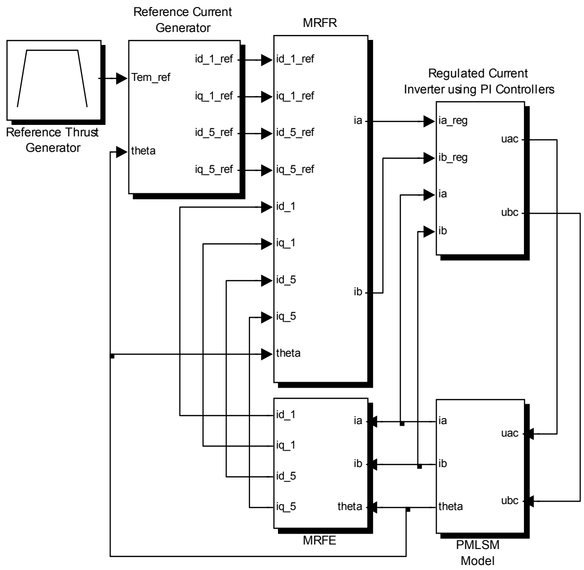

Figure 2: Block diagram of thrust control of a PMLSM with multiple synchronous reference frames using PI controllers.

Figure 3 presents an existing technique for the multiple reference frame estimator (Chapman 2000). This technique gives quite suitable results for diverse applications, such as control of magnetic levitation and propulsion (Liu 1998), fault detection in induction motors (Cruz 2005) or power factor correction in active filter (Park 2000).

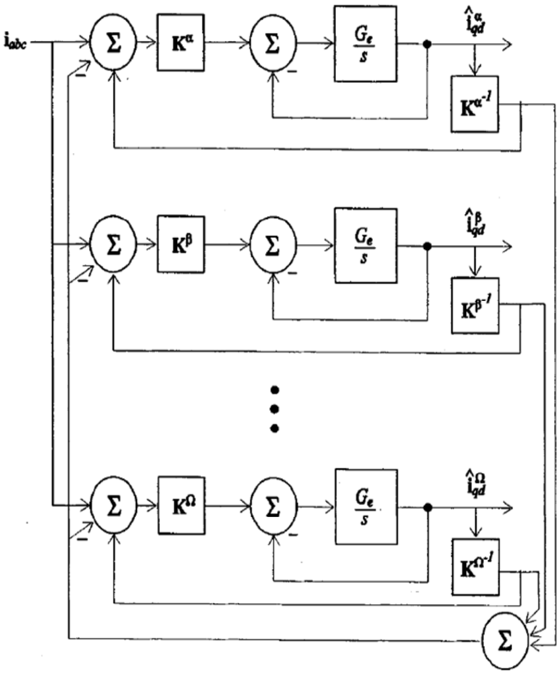

Figure 3: Structure of a Multiple Reference Frame Estimator (MRFE).

The algorithm of the MRFE in Figure 3 is based on the following equation (Chapman 2000):

$$\frac{1}{G_e}\frac{d}{dt}\tilde{i}_{dq} = K^x\left[i_{abc} + \left(K^x\right)^{-1}\tilde{i}^x_{dq} - \sum_{m\in N}\left(K^m\right)^{-1}\tilde{i}^m_{dq}\right] \qquad (4)$$

An important assumption is to consider that the estimator is faster than the regulator:

$$\frac{d}{dt} i^x_{dq} = 0, \quad so \quad \frac{d}{dt}\left(\tilde{i}^x_{dq} - i^x_{dq}\right) = -nG_e\left(\tilde{i}^x_{dq} - i^x_{dq}\right), \quad \forall x \in N \qquad (5)$$

Finally, we can notice in Equation 5 that the solution has an exponential convergence and is stable. Figure 4 validates the approach with an MRF Estimator using 2 frames: one on the fundamental and one on the 5th harmonic of the measured current.

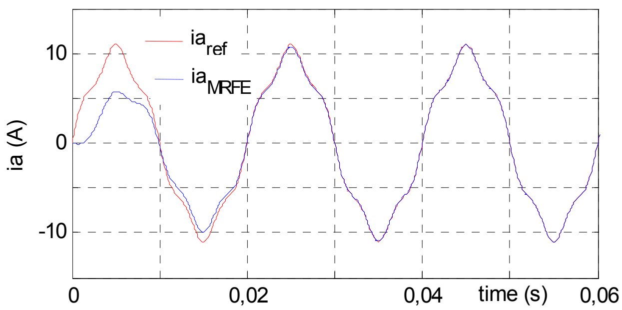

Figure 4: Simulation of the reconstructed current *ia* using an MRF Estimator.

2.2 *The controller tuning*

An example of the structure of the multiple reference frames regulator MRFR is represented in Figure 5 (Chapman 2000). The principle of this MRFR is to regulate the harmonics values of the estimated currents close to those of the reference currents.

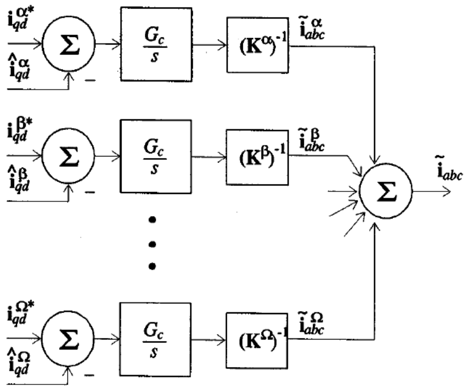

Figure 5: Structure of a Multiple Reference Frame Regulator (MRFR).

The generation of the reference currents in the multiple synchronous reference frames has many freedom degrees: with only one reference thrust, *2n* currents need to be generated for *n* frames. So, many works give an energetic approach by considering the reduction of the loss induced by currents to generate these *2n* reference currents (Chapman 1999b, and Wu 2005). An example is given in Equation 4:

$$\begin{cases} i_{d1} = 0; \quad i_{q1} = \dfrac{T_{eref}\cdot 1}{\sqrt{\dfrac{3}{2}}\cdot N_p \cdot \hat{\phi}_f \cdot \sqrt{1-\sum_{x\in n}\lambda_x^2}}, \cdots \\ i_{dn} = 0; \quad i_{qn} = \dfrac{T_{eref}\cdot(-\lambda_5)}{\sqrt{\dfrac{3}{2}}\cdot N_p \cdot \hat{\phi}_f \cdot \sqrt{1-\sum_{x\in n}\lambda_x^2}} \end{cases} \qquad (6)$$

So, for minimizing Joule losses: $i_{d1} = \cdots = i_{dN} = 0$.

The system can be linearized versus all operating points to check global stability and pole location, that gives an optimal G_c value (Chapman 1999a).

For the MRFR technique, the inverter needs a feedback control to regulate the currents, using either hysteresis controllers or PI controllers.

3 THE RESONANT CONTROLLER TUNING

3.1 *Control Structure*

The control structure of the diphase reference frame with resonant controllers (Degobert 2006) can be:

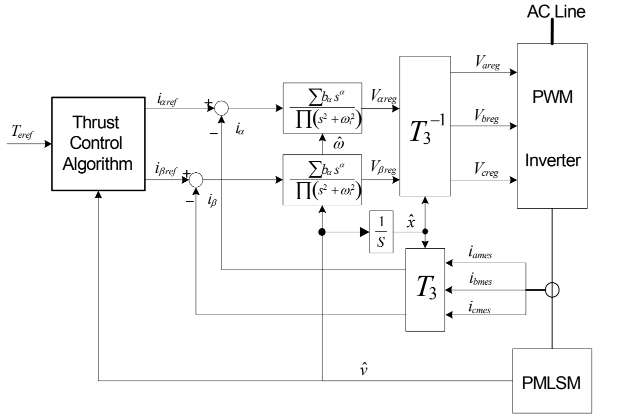

Figure 6: Block diagram of the thrust control of a PMLSM with multi-variable-frequency resonant controllers.

Wherein T_{eref} = the reference thrust; and $i_{\alpha ref}$, $i_{\beta ref}$ = the reference excitation currents.

The general transfer function of a multiple-frequency resonant controller is given by:

$$C(s)=\frac{\sum_{j=0}^{2k} b_j s^j}{\prod_{i=1}^{k}\left(s^2+\omega_i^2\right)} \tag{7}$$

Wherein k denotes the number of associated resonant elements and ω_i corresponds to the concerned resonant frequencies. The design of these controllers relies on the parameters of the respective regulated systems and the configurations of the respective commands. The tracking of the reference currents and the rejection of disturbances from non-sinusoidal back-EMF can be simultaneously realized with two resonant controllers in series.

So it's important to specify that the back-electromotive compensation is directly included in the resonant controller, and doesn't need a feed forward compensation (Remy 2006).

3.2 *The resonant controller tuning*

In considering the self and mutual inductances as time constants, the PMLSM model can be treated as two decoupled subsystems in (α-β) axes. Therefore, the two controllers should be separately designed according to their respective resistances and inductances. So, the reference excitation currents ($i_{\alpha ref}$ and $i_{\beta ref}$) are generated according to the mover position x and to the reference thrust T_{eref}, which are given by Equation 8 and implemented in the "Thrust Control Algorithm" block.

$$\begin{cases} i_{\alpha ref} = \dfrac{T_{eref}\cdot\left[-\sin(\theta)+\lambda_5\cdot\sin(5\theta)\right]}{\sqrt{\dfrac{3}{2}}\cdot N_p\cdot\hat{\phi}_f\cdot(1-\lambda_5^2)} \\ i_{\beta ref} = \dfrac{T_{eref}\cdot\left[\cos(\theta)+\lambda_5\cdot\cos(5\theta)\right]}{\sqrt{\dfrac{3}{2}}\cdot N_p\cdot\hat{\phi}_f\cdot(1-\lambda_5^2)} \end{cases} \tag{8}$$

Wherein T_{eref} = the reference thrust; λ_5 = relative harmonics of back electromotive force; $N_p = \pi/\tau_p$ the electrical position constant and $\hat{\phi}_f$ = maximum value of magnet flux per phase.

In our case, the two controllers have identical structures with two resonant frequencies – the fundamental and the 5th harmonic. Two frequency resonant controllers produce infinite gains as shown on the bode diagrams of the open-loop transfer function of the control system at the concerned frequencies (ω, 5ω), which ensures that the steady-state error at these frequencies can be completely eliminated, Figure 7:

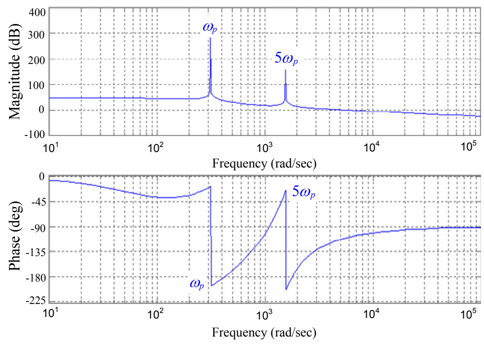

Figure 7: Bode diagram of open-loop transfer function

The coefficients of controller b_α can be determined by using a pole assignment technique (Guillaud 1999) depicted in Figure 8.

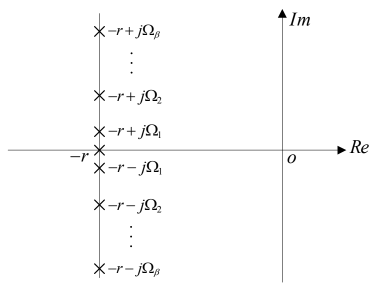

Figure 8: Pole locations of the closed-loop system identified by proposed criterion polynomial

Then, the coefficients of controller b_α can be identified from the characteristic polynomial of the closed-loop transfer function of the system by a criterion polynomial (Zeng 2004) as in Equation 9:

$$P_{GSM}(s)=(s+r)\prod_{i=1}^{\beta}\left[\left(s+r+j\Omega_i\right)\left(s+r-j\Omega_i\right)\right] \tag{9}$$

4 COMPARISON OF RESULTS

4.1 *Results of the hysteresis and PI controllers*

The control structure of the multiple synchronous reference frames with PI controllers is represented in Figure 2:

The thrust reference is a trapezoidal waveform with a rising time of 5ms, a holding time of 600ms and a falling time of 2ms. In machine-tools application for positioning system, these values correspond to a classic thrust profile called Jerk limited profile (Groß 2001). Results with the MRF technique using hyteresis controllers are shown in Figure 9. Results with the MRF technique using PI controllers are shown in Figure 10:

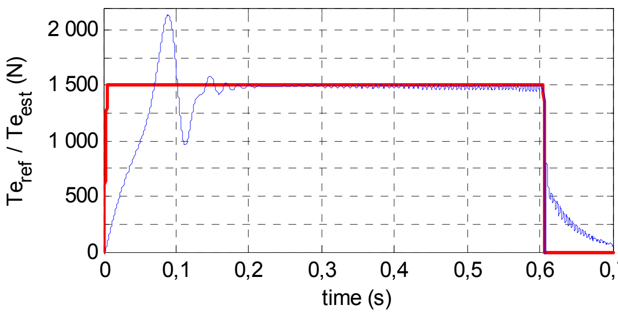

Figure 9: Reference thrust and estimated thrust with Synchronous Multiple Reference Frames using PI controllers.

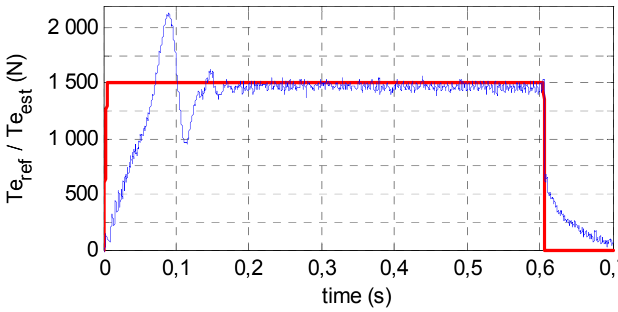

Figure 10: Reference thrust and filtered estimated thrust with Synchronous Multiple Reference Frames using Hysteresis controllers.

We can notice that both controllers: hysteresis and PI controllers have the same response time of about 150ms. But with the hysteresis controller, the estimated thrust is stable and noisy, and with PI controllers, the estimated thrust is less noisy but some ripple force appears due to a sinusoidal error of the MRFE that can not be compensated by the PI controller, which can be a stability problem for the system. So, the low time response is only due to the MRF Estimator, which is not able to track the fast reference changes.

The gain value in the MRFE of G_e is settled on the highest possible value to hold a stabilized response of the estimator, and so the shortest time response. Here, G_e = 150 s^{-1}. Furthermore, a lower value of G_e reduces the thrust overshoot, but increases the response time of the MRFE. After all, the fastest response time is up to 150ms.

The Synchronous Multiple Reference Frames using PI controllers give suitable results for control of linear synchronous motors (Faiz 2002). However, the MRFER is not adapted for machine-tools application, especially for the industrial current closed-loop control. Indeed for the current closed-loop control, such applications request a time response of about 10ms to guaranty an independent speed closed-loop control (Groß 2001).

4.2 *Validation of the resonant controllers*

The control scheme depicted in Figure 11 is implemented in a dSPACE DS1005 real-time digital control card to drive the PMLSM through an IGBT inverter.

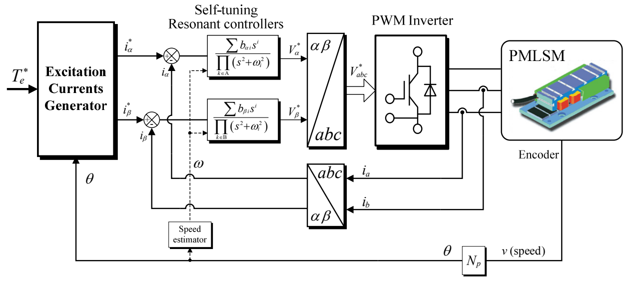

Figure 11: The test bench with a Rexroth LSP120C

4.3 *Presentation of the test bench*

The proposed approach is experimentally verified on a laboratory test system equipped with a Rexroth LSP120C linear motor in Figure 12:

Figure 12: The test bench with a Rexroth LSP120C

We have used a Heindenhain exposed linear encoder with a grating period of 20µm, which is a high precision incremental encoder, to detect the mover position. Table 1 lists the specifications of the test bench parameters:

Table 1: Specifications of test bench parameters

Parameter names	Parameter values
Rated current; Maximum current	51 [A]; 175 [A]
Rated voltage	220 [V]
Rated thrust; Maximum thrust	3100 [N]; 7800 [N]
Attraction force	20100 [N]
Pole pitch	τ_p = 37.5 [mm]
Electrical position constant	N_p = 83.8 [rad/m]
Armature resistance	R = 1.1 [Ω]/ phase
Cyclic inductance	L_{s0}-M_{s0} = 6.0 [mH]
Max value of magnet flux per phase	Φ_f = 0.637 [Wb]
Harmonic values of back-EMF	λ_1 = 1; λ_5 = 0.0267
IGBT switching frequency	f_c = 10 [kHz]
Pole assignment value	r = 1000

Simulation and experimentation of a thrust control with diphase reference frames using resonant controllers are represented in Figure 13.

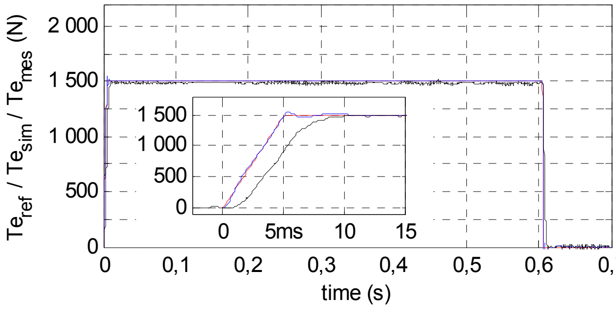

Figure 13: Reference thrust and estimated thrust with diphase reference frames using resonant controllers.

The response time of the estimated thrust on the simulation is close to 5ms. For the experimentation, the estimated thrust presents a time lag of 2ms because of the Analog to Digital Converter in the speed measurement and the time lag of the inverter.

The thrust overshoot is about 3% of the reference thrust.

Reference currents and simulated currents are shown in Figure 14:

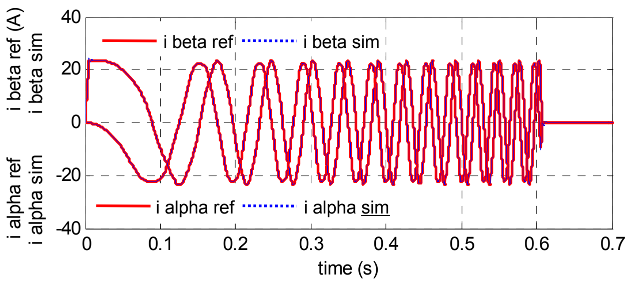

Figure 14: Reference, simulated and measured current with diphase reference frames using resonant controllers.

The estimated currents follow the reference currents perfectly. That validates the effectiveness of the resonant controller in diphase reference frames.

5 CONCLUSIONS

The control structures of the synchronous multiple reference frames with hysteresis controllers and PI controllers have been simulated. Results show that the MRF Estimator requests more than 150ms to converge. This method is stable and could be implemented for steady-state applications with speed control. But for positioning systems with high dynamics, such as machine-tools applications, the tracking errors of the currents limited disallow a good thrust control.

The control structure of the diphase reference frames with resonant controllers has been presented and gives very effective results: even if there are fast reference changes, thrust responses are about 5ms.

Nevertheless, both methods require good knowledge of the harmonic ranks of back-electromotive forces for the current reference generator.

Future works will be focused on the compensation of cogging force of the PMLSM, on the theory of robustness and anti-windup tuning theory for resonant controllers.

6 REFERENCES

Chapman, P.L. & Sudhoff, S.D. 1999a. Optimal control of permanent-magnet AC machine drives with a novel multiple reference frame estimator/regulator. *Proc. 34th IAS Annual Meeting. Conf. Record of the 1999 IEEE Industry Applications Conference* 4: 2567-2573, October 1999.

Chapman, P.L. & Sudhoff, S.D. & Whitcomb, C.A. 1999b. Optimal Control Strategies for Non-Sinusoidal Permanent-Magnet Synchronous Machine Drives. *IEEE Transactions on Energy Conversion* 14(4):1043-1050, December 1999.

Chapman, P.L. & Sudhoff, S.D. 2000. A multiple reference frame synchronous estimator/regulator. *IEEE Transactions on Energy Conversion* 15(2): 197-202, June 2000.

Cruz, S.M.A. & Cardoso, A.J.M. 2005. Multiple Reference Frames Theory: A New Method for the Diagnosis of Stator Faults in Three-Phase Induction Motors. *IEEE Transactions on Energy Conversion* 20(3): 611-619, September 2005.

Degobert, P. & Remy, G. & Zeng, J. & Barre, P.J. & Hautier, J.P. 2006. High Performance Control of the Permanent Magnet Synchronous Motor using Self-Tuning Resonant Controllers. *Proc. 38th South-eastern Symposium on System Theory (IEEE-SSST 2006)* Tennessee, Cookeville, USA, March 2006.

Faiz, J. & Rezaei-Alam, B. 2002. Control of a linear Permanent Magnet Synchronous Motor using Multiple Reference Frame Theory. *Proc. 17th International Conference on Magnetically Levitated Systems and Linear Drives (MAGLEV 2002)*, Lausanne, September 2002, Switzerland.

Fitzgerald, A.E. & Kingsley, C. & Umans, S. 2003. *Electric Machinery*. (6 ed), McGraw-Hill.

Gieras, J.F. & Piech, Z.J. 2000. *Linear Synchronous Motors, Transportation and Automation Systems*. CRC Press.

Groß, H. & Hamann, J. & Wiegärtner, G. 2001. *Electrical Feed Drives for Automation Technology - Basics, Computation, Dimensioning*. VCH Publishers.

Guillaud, X. & Vandecasteele, F. & Wulverick, M. & Hautier, J.P. 1999. New Concept of Corrector for the Control of Alternative Quantities. *Proc. 8th European Conference on Power Electronics and Applications (EPE'99)* Lausanne, Switzerland, September 1999.

Hung, J.Y. & Ding, Z. 1992. Minimization of Torque Ripple in Permanent-Magnet Motors: A Closed Form Solution. *Proc. of the 18th IEEE Industrial Electronics Conference* 1: 459-463, 1992.

Liu, C.T. & Hsu, S.C. 1998. Analysis of linear electromagnetic motion devices by multiple-reference frame theory. *IEEE Transactions on Magnetics* 34(4): 2063-2065, July 1998.

Park, S. & Han, S.B. & Jung, B.M. & Choi, S.H. & Jeong, H.G. 2000. A current control scheme based on multiple synchronous reference frames for parallel hybrid active filter. *Proc. 3th International of Power Electronics and Motion Control Conference (PIEMC 2000)* 1: 218-223, 15-18 August 2000.

Remy, G. & Zeng, J. & Barre, P.J. & Degobert, P. & Hautier. J.P. 2005. Non-Sinusoidal Electromotive Force Compensation of the PMLSM with Multiple-Frequency Resonant

Controller. *Proc. 5th International Symposium on Linear Drives for Industry Applications (LDIA 2005)* Awaji Yumebutai, Hyogo, Japan, September 2005.
Remy, G. & Barre, P.J. & Hautier, J.P. 2006. Application of the Causal Ordering Graph to Synchronous Motors, Part II: Control Design, *WSEAS Transactions on Power Systems* 2(1):532-529, February 2006.
Wu, A.P. & Chapman, P.L. 2005. Simple expressions for optimal current waveforms for permanent-magnet synchronous machine drives. *IEEE Transactions on Energy Conversion* 20(1): pp: 151-157, March 2005.
Zeng, J. & Remy, G. & Degobert, P. & Barre, P.J. 2004. Thrust Control of the Permanent Magnet Linear Synchronous Motor with Multi-Frequency Resonant Controllers. *Proc. 18th International Conference on Magnetically Levitated Systems and Linear Drives (MAGLEV 2004)* 2: 886-896, Shanghai, October 2004, China.