Speed Sensorless Control of a Long-Stator Linear Synchronous-Motor arranged by Multiple Sections

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***Abstract* – Linear Permanent Magnet (PM) Motors have become a viable alternative for material handling and processing systems in the industry, mainly because of its higher dynamic response, robustness and accuracy. For long stators, the position sensor, which extents along the carriageway, becomes a costly part of the system. In addition, for long carriageways, the stator is divided in several sections increasing sensing complexity. Therefore, sensorless methods are of higher concern than in rotative motors. In this paper, a speed sensorless control of a long-stator linear synchronous motor arranged by multiple sections is presented. This method uses an EMF observer for each active section (i.e. where the mover is and the subsequent). Then, based on the addition of the observed EMF a single speed and position observer is implemented for the mover. Finally, using an experimental setup, validation results are attained and presented.**

I. INTRODUCTION

Linear motion, in industrial applications, is usually achieved by rotative motors with a rotative-to-linear conversion mechanism like belts and pulleys, racks and pinions or screw systems. Linear motors have become a viable alternative to this. They have a higher dynamic response, no backslash, higher efficiency, but are still more expensive. This paper deals with linear synchronous motors with Permanent Magnets (PM). They are of special interest because of their high efficiency, high power density and because they allow a higher air gap. Among the different possible configurations, a motor with a long stator (carriageway) and a short mover (vehicle) is considered. This configuration allows a passive mover avoiding brushes or cables connected to it, which would reduce robustness and travel distance.

For long distances, the stator is arranged by several electrically independent sections [1]. This allows reducing the reactive power production by driving only the section in which the mover is. Additionally, this arrangement allows handling several vehicles in the same carriageway.

In order to drive the motor it is required to know the movers position. The position can be acquired by position sensors or by sensorless methods, which indirectly derive the position from the measured stator voltage and current [2]. Avoiding position sensors is an important issue because they are rather expensive and they reduce the reliability of the whole system. Rotative motors require only one sensor in the shaft, but in linear motors, this sensor is dispersed along the carriageway. Therefore avoiding position sensors in linear motors is even more important than in rotative motors.

Several sensorless methods have been proposed for rotative synchronous motors. They can mainly be classified in two groups. One group is based on estimation of Electro Motive Force (EMF) to get the rotor position, e.g. [3]-[5]. While the EMF is proportional to the mover's speed, it is not possible to estimate the position for low speed operation. The other group is based on the measurement of position dependent inductances [6]-[7]. Inductance varies with position in salient movers or when mover's flux produces a significant saturation in the stator.

Some authors have proposed sensorless methods for linear synchronous motors e.g. [8], however they deal with single section motors. In this paper, a sensorless method for linear synchronous motor with multiple sections is proposed. An EMF observer is used for each active section (i.e. current and subsequent) and a single position observer for the mover.

This paper is organized as follows. In Section II the linear synchronous motor is described and modelled. In Section III the speed and position observer is proposed. In Section IV experimental results are presented. Finally, in Section V, some conclusions are drawn.

II. MOTOR MODEL

Fig. 1 shows a scheme of one section of the linear synchronous motor. The pole pitch is designated by τ_p and the mover's displacement axes by x. Each section has 13 poles arranged in 39 slots, while the mover has 3 poles. Consecutive sections are connected with a 180° phase shift.

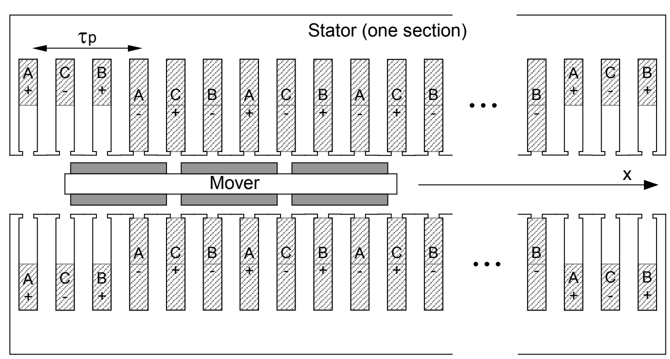

Fig. 1. Scheme of one section of the linear synchronous motor.

In order to obtain a model of the described motor, the Magnetic Equivalent Circuit (MEC) method was used [9]. This method allows getting a lumped parameters model of the motor starting from its geometry and winding distribution. The attained model transformed to a space-vector system in the stator reference frame (i.e. $\alpha\beta$ variables), yields,

$$\mathbf{u} = \mathbf{i}\, R + \frac{d\,\boldsymbol{\lambda}}{dt} \qquad (1)$$

where $\mathbf{u}$ and $\mathbf{i}$ are the stator voltage and current, respectively; R is the stator resistance; and $\boldsymbol{\lambda}$ is the flux linkage.

Two terms can be considered to form the flux,

$$\boldsymbol{\lambda} = \boldsymbol{\lambda}_{\mathbf{L}} + \boldsymbol{\lambda}_{\mathbf{PM}}(x) \qquad (2)$$

One term is current dependent,

$$\boldsymbol{\lambda}_{\mathbf{L}} = \mathbf{L}\,\mathbf{i} \qquad (3)$$

where $\mathbf{L}$ is the stator inductance matrix, while the other term depends on the mover position.

Equations (1)-(2) can be rearranged as state equations,

$$\frac{d\,\boldsymbol{\lambda}_{\mathbf{L}}}{dt} = \mathbf{u} - \mathbf{i}\, R - \mathbf{e} \qquad (4)$$

The term $\mathbf{e}$ is the EMF, which can be obtained by differentiating $\boldsymbol{\lambda}_{\mathbf{PM}}(x)$ with respect to time,

$$\mathbf{e} = \frac{d\,\boldsymbol{\lambda}_{\mathbf{PM}}}{dt} = \boldsymbol{\gamma}(\theta)\,\omega \qquad (5)$$

where the electrical angular position is defined as $\theta = x\,\pi/\tau_p$, and the electrical angular speed as $\omega = d\,\theta/dt$. The function $\boldsymbol{\gamma}(\theta)$, which is the EMF normalized per speed unit, was numerically obtained by the MEC method. Fig. 2 shows this function for one section and for the complete position span. It can be seen, in this figure, that the magnitude attenuates when the mover leaves the corresponding section.

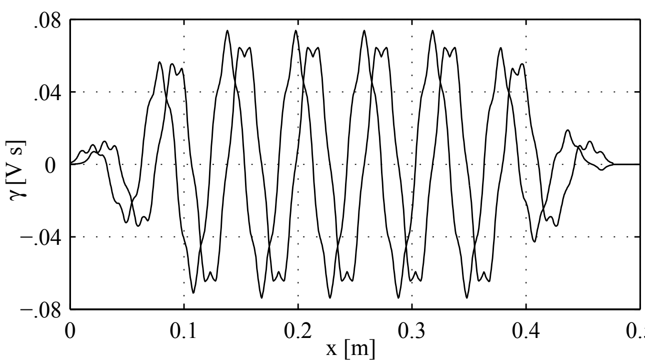

Fig. 2. Normalized EMF space-vector ($\boldsymbol{\gamma}(x) = \mathbf{e}/\omega$) as a function of the position, obtained by model, for one section.

The normalized EMF space-vector ($\boldsymbol{\gamma}$) was also measured at the experimental set-up, and is displayed in Fig. 3.

When the mover is completely inside the section, it can be approximated as follows,

$$\boldsymbol{\gamma}(\theta) \cong f_m \begin{bmatrix} -\sin\theta - m\sin 5\theta \\ \cos\theta - m\cos 5\theta \end{bmatrix} \qquad (6)$$

Parameters f_m and m depend on the permanent magnets and mechanical dimensions.

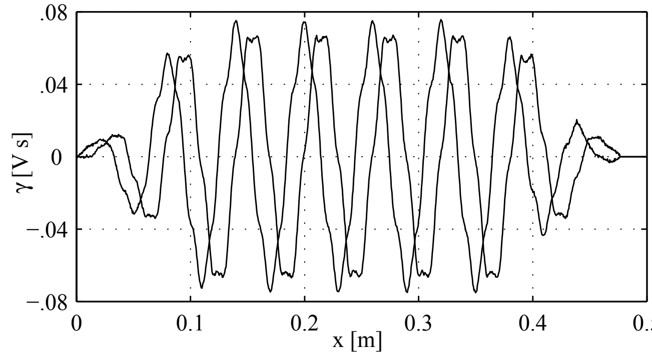

Fig. 3. Normalized EMF space-vector as a function of the position, obtained experimentally, for one section.

For one mover and multiple sections, it is useful to analyse the addition of all section's EMF. Fig. 4 shows the waveform resulting from adding the EMF of three sections. It can be seen that the waveform magnitude become reduced in the section transition (i.e. $x = 0.05\,m$ and $x = 0.45\,m$). Besides this magnitude reduction, the EMF addition can be well modelled by (6).

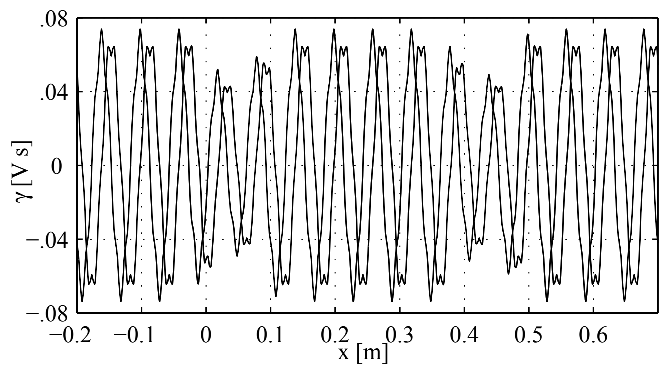

Fig. 4. Normalized EMF space-vector addition of multiple sections.

The electromagnetic force on the mover is,

$$F = \frac{3}{2}\frac{\pi}{\tau_p}\boldsymbol{\gamma}(\theta)^T\,\mathbf{i} \qquad (7)$$

and the mover's dynamics,

$$\frac{dx}{dt} = v \qquad (8)$$

$$\frac{dv}{dt} = \frac{1}{M}F - \frac{B}{M}v - F_L \qquad (9)$$

where v is the speed of the mover; M is the mass; B is the friction coefficient; and F_L is the load force (in which cogging force can be included).

In order to drive the linear motor, one inverter is used for each section [1]. The field-orientation control scheme is used. As long as the mover is completely inside one section, only the corresponding inverter is active. On section transitions, both involved sections are driven with the complementary current.

III. SPEED AND POSITION OBSERVER

The main strategy to estimate the speed and position of a multi-section arrangement of the linear motor is to use two EMF observers, one for each active section. Then, the addition of both EMF space vectors is used to get the speed and position of the mover.

First, the EMF observers are designed. As the speed changes slowly, compared to electrical variables, it is assumed constant in order to design the observer [4]. Moreover, in seek of simplicity, the flux linkage due the permanent magnets, $\boldsymbol{\lambda}_{\mathbf{L}}$, is assumed sinusoidal with constant magnitude. Consequently (5) becomes,

$$\mathbf{e} = \omega\, f_m \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \tag{10}$$

In order to extend the electrical state equation (4), the time derivative of (10) is calculated,

$$\frac{d\,\mathbf{e}}{dt} = \omega^2\, f_m \begin{bmatrix} -\cos\theta \\ -\sin\theta \end{bmatrix} = -\mathbf{J}\,\omega\,\mathbf{e} \tag{11}$$

with $\mathbf{J} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$.

Based on (4) and (11), a full order state observer is proposed,

$$\frac{d\,\hat{\boldsymbol{\lambda}}_{\mathbf{L}}}{dt} = \mathbf{u} - \mathbf{i}\,R - \hat{\mathbf{e}} + \mathbf{G_1}\left(\mathbf{i} - \mathbf{L}^{-1}\hat{\boldsymbol{\lambda}}_{\mathbf{L}}\right) \tag{12}$$

$$\frac{d\,\hat{\mathbf{e}}}{dt} = -\mathbf{J}\,\omega\,\hat{\mathbf{e}} + \mathbf{G_2}\left(\mathbf{i} - \mathbf{L}^{-1}\hat{\boldsymbol{\lambda}}_{\mathbf{L}}\right) \tag{13}$$

By assuming ω known and constant, the system becomes linear, and gains $\mathbf{G_1}$ and $\mathbf{G_2}$ can be selected by pole placement. Poles are placed to have high damping ratio and to be faster than the mechanical dynamic, for the whole range of speed.

As stated before, the observer (12)-(13) is implemented twice, one for each active section. The addition of the estimated EMF is used for the correction term of the speed and position observer. This observer is defined as,

$$\begin{aligned} \frac{d\,\hat{\omega}}{dt} &= -K_I\, c \\ \frac{d\,\hat{\theta}}{dt} &= \hat{\omega} - K_P\, c \end{aligned} \tag{14}$$

and the correction term is,

$$c = \begin{bmatrix} \cos\hat{\theta} & \sin\hat{\theta} \end{bmatrix} \hat{\mathbf{e}} \tag{15}$$

In order to analyse the action of the correction term, equation (10) is substituted into (15), yielding,

$$c = \hat{\omega}\, f_m\, \sin(\hat{\theta} - \theta) \cong \hat{\omega}\, f_m\, (\hat{\theta} - \theta) \tag{16}$$

For low acceleration and positive values of K_P and K_I, the stable equilibrium points of the observer are,

$$\hat{\omega} = \omega \tag{17}$$

$$\hat{\theta} = \begin{cases} \theta + (2k)\pi & \text{for}\ \omega > 0 \\ \theta + (2k+1)\pi & \text{for}\ \omega < 0 \end{cases}$$

Convergence speed to the equilibrium point can be adjusted with K_P and K_I. Therefore, linearization of the observer error dynamic is used.

In Fig. 4 a block diagram of the proposed sensorless speed control for a linear synchronous motors is shown. Each section of the linear motor is driven by its own inverter [1].

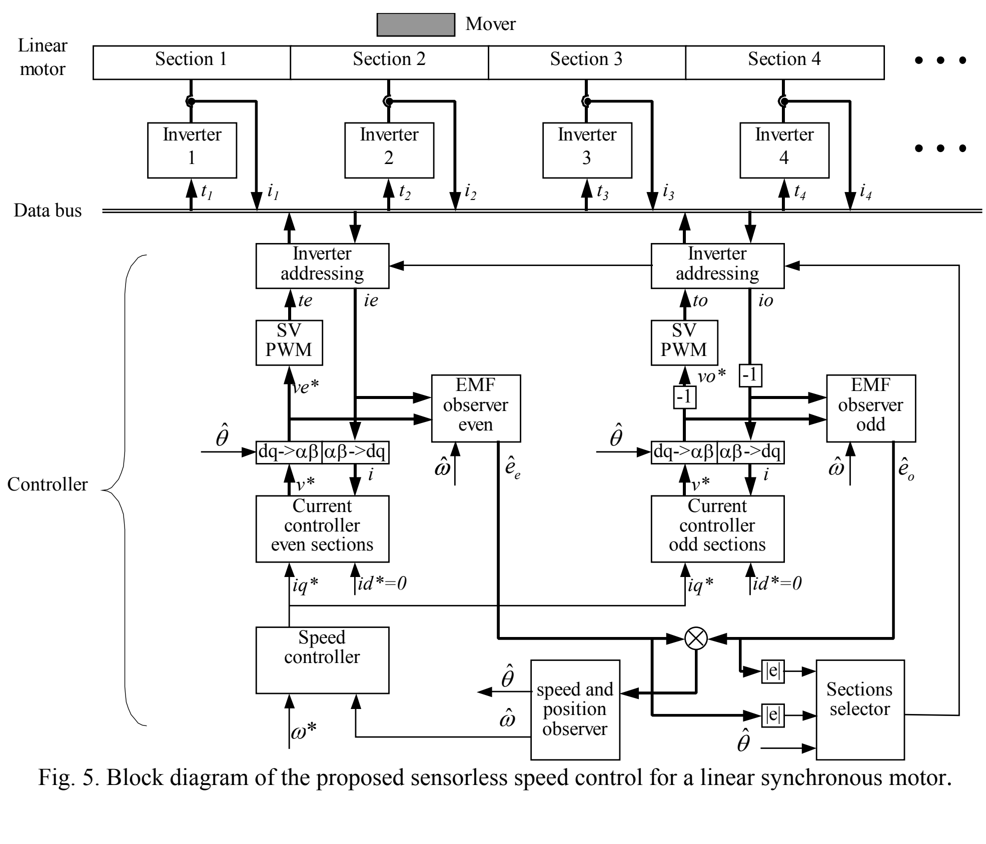

Fig. 5. Block diagram of the proposed sensorless speed control for a linear synchronous motor.

The inverters are connected to a data bus. When an inverter is addressed by the controller, it retrieves the SV-PWM switching times, and replies with the actual current values.

Only two sets of d-q-current controllers are implemented, one for even sections, and the another for odd sections. Depending on the mover's position, they are directed to the corresponding inverters.

Similarly, there are two EMF observers, one for even sections and other for odd sections. Its inputs are the reference voltage and the actual current, retrieved from the corresponding current controller, and the estimated speed, taken from the speed observer. The reference voltages from the current controller are compensated for dead time and switches voltage drop [10]. Both EMF observer outputs are added and used as input for the speed and position observer.

The estimated speed and position are used as feedback for the speed controller and for the reference frame transformation, respectively. The speed controller output, which is the quadrature current reference, feeds both current controllers.

In order to direct the current controller to the corresponding inverter, the estimated position is used. However, for this purpose, the estimated position has to be related to an absolute reference. This is achieved with the magnitude of the observed EMF, which falls to zero when the mover leaves the current section.

To avoid spikes in the observed values, while switching the current controller from one section to another, the current is forced smoothly to zero before the switching, and thereafter returned smoothly to the reference value. This will not affect the electromagnetic force production because switching takes place while the mover is outside the involved sections.

IV. EXPERIMENTAL RESULTS

An experimental setup was used to validate the proposed sensorless method. It is composed by a linear motor, four inverters, and a controller implemented with a x86 PC.

The linear PM synchronous motor is arranged by eight sections in a closed circular path as shown in Fig. 6. Each section is as described in Fig. 1. Table I shows the motor parameters.

TABLE I
MOTOR PARAMETERS

Nominal current	$I_N = 52$ A	Poles per section	13
Peak current	$I_{MAX} = 104$ A	Sections	8
Stator resistance	$R = 1.1$	Mover Mass	$M = 12.5$ Kg
Stator inductance	$L = 6.4$ mHy	Flux	$f_m = 0.068$ Vs
Pole pitch	$\tau_p = 0.03$m	5th harmonic	$m = 0.089$

As the motor circular path is vertically situated, the mover offers a position dependent load as shown,

$$F_L = 122.5\sin(\theta/52) \quad [\text{N}] \tag{18}$$

In Fig. 7 to Fig. 11 results of one experimental test are shown. In this test, the speed reference is set to 1.17 m/s and stepwise changed to 1.95 m/s at time t = 1 s.

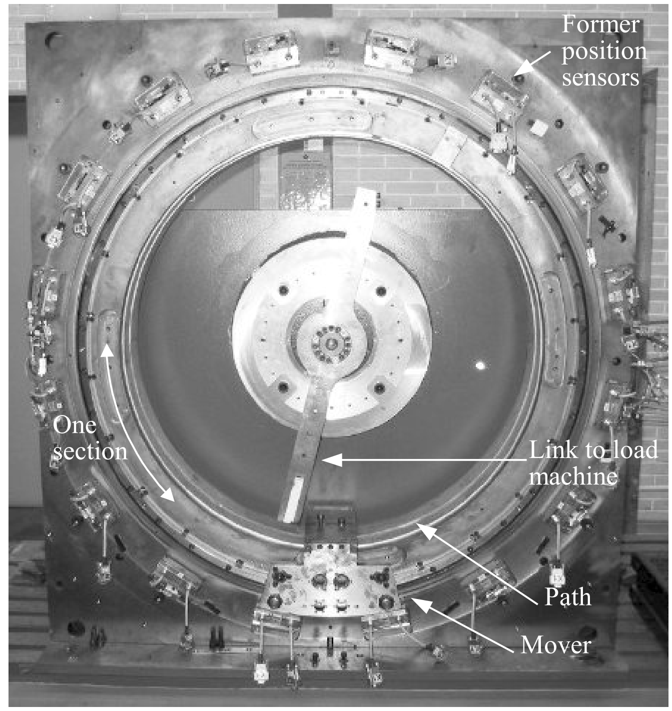

Fig. 6. Experimental linear motor arranged by eight sections in closed circular path.

In Fig. 7 the estimated EMF resulting from the even-sections and odd-sections observers are shown. These variables are in the stator reference frame. The same EMF variables are shown in Fig. 8 but in the estimated rotor reference frame.

The quadrature current values for the even and odd active sections are shown in Fig. 9. Some points, in which current is forced to zero for section switching, can be appreciated in this figure.

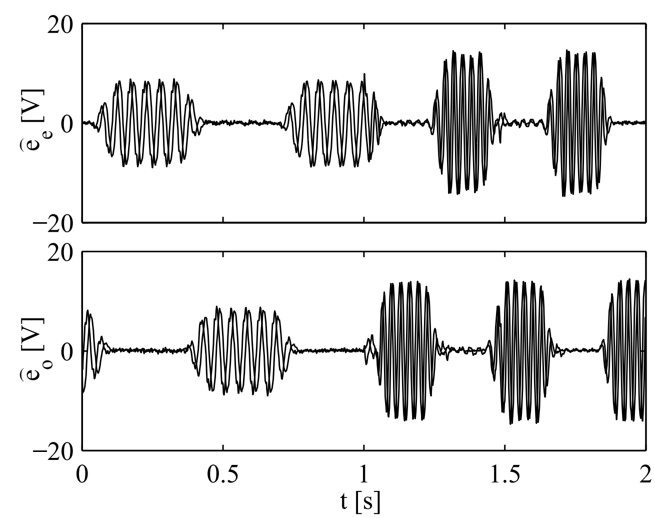

Fig. 7. Observed EMF in the stator reference frame, a) even sections, b) odd sections.

The actual and the estimated speed of the mover are shown in Fig. 10. It can be observed that estimated value agrees well with the actual value. However, speed regulation by itself is hardly affected by a ripple. This is due to the high cogging-force present in this motor, and by the force reduction at section transitions. As shown in Fig. 1, lower winding density in the first and last three slots results in a force reduction at section transitions, this is also manifested by an EMF reduction (see Fig. 4).

Finally, in Fig. 11 the electrical angle error, are shown for the same test.

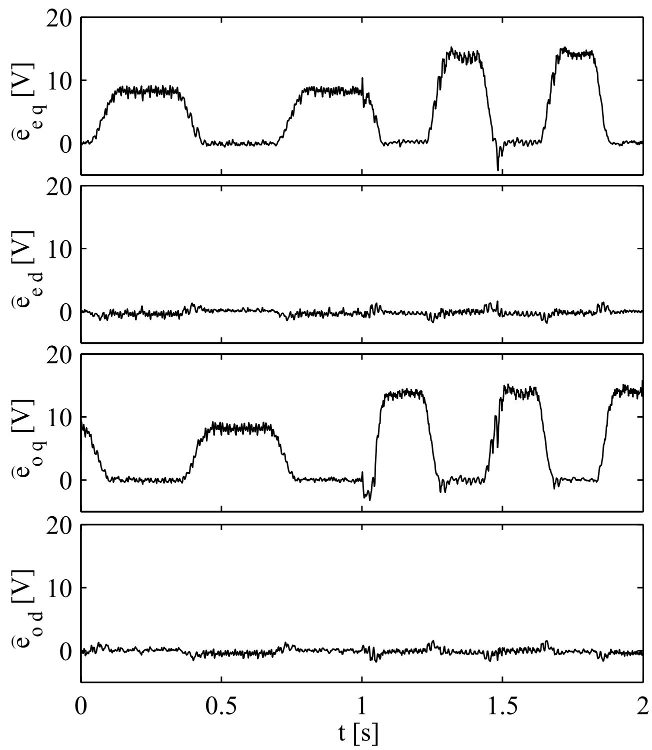

Fig. 8. Observed EMF in the estimated rotor reference frame, a) even sections, b) odd sections.

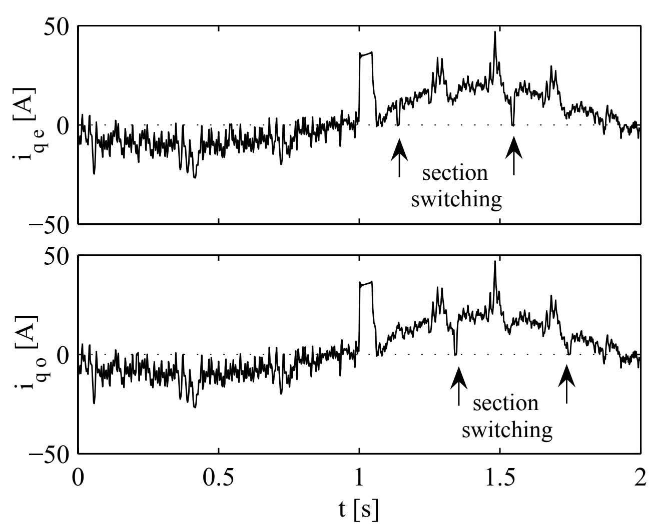

Fig. 9. Actual q-current a) even sections; b) odd sections.

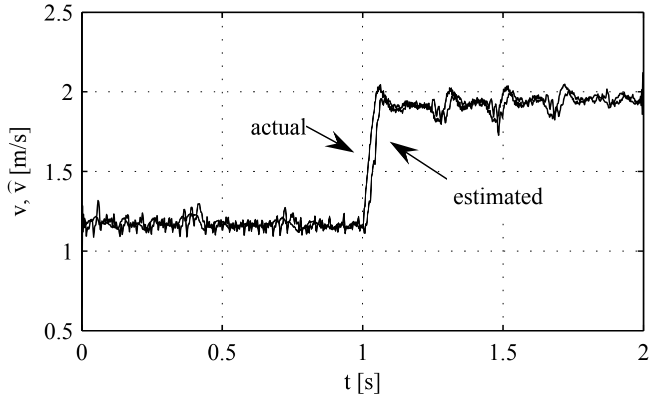

Fig. 10. Actual (solid) and observed (dash) linear speed.

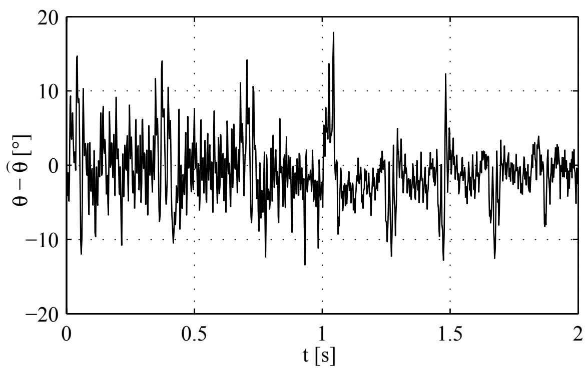

Fig. 11. Electrical angle error.

V. CONCLUSIONS

A method for control of Linear Synchronous-Motors without speed or position sensors was proposed. It allows speed control of the mover in a carriageway arranged by multiple sections. In addition, it provides the means to select the sections to be driven.

Experimental tests, using the proposed method in closed loop, were carried out with an eight sections linear motor. Tests results show high agreement between observed and actual values of speed and position, even when the mover is loaded. These results validate the model simplifications introduced for the EMF observer and the overall proposal.

VI. ACKNOWLEDGMENT

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VII. REFERENCES

[1] R. Benavides and P. Mutschler, "Controlling a System of Linear Drives" in *Proceedings of the IEEE Power Electronics Specialists Conference PESC 2005*, 12-16 June 2005, Recife, Brazil, pp. 1587-1593.

[2] K. Rajashekara, A. Kawamura and K. Matsuse, *Sensorless Control of AC Motor Drives*, IEEE Press, New York, 1996.

[3] Y-C. Son, B-H. Bae and S-K. Sul, “Sensorless operation of permanent magnet motor using direct voltage sensing circuit” in *Proceedings of the Industry Applications Conference, 2002. 37th IAS Annual Meeting*. 13-18 Oct. 2002, pp.1674-1678, vol.3.

[4] J-S. Kim and S-K. Sul, “High Performance PMSM Drives without Rotational Position Sensor using Reduced Order Observer” *in Proceedings of the Industry Applications Conference. 30th IAS Annual Meeting*. 8-12 Oct. 1995, pp. 75-82, vol.1.

[5] C. De Angelo, G. Bossio, G. Garcia, J. Solsona, M.I. Valla, “Sensorless speed control of permanent magnet motors with torque ripple minimization”, *in Proceedings of the IEEE-IES Annual Conference IECON 02.* 5-8 Nov. 2002 pp. 680-685, vol.1

[6] M.J. Corley and R.D. Lorenz, "Rotor position and velocity estimation for a salient-pole permanent magnet synchronous machine at standstill and high speeds", *IEEE Transactions on Industry Applications*, Vol. 34, No. 4, 784-789, July-Aug. 1998.

[7] M. Schroedl, "Sensorless control of ac machines at low speed and stand-still based on the INFORM method", *in Conference Record IEEE-IAS Annual Meeting*, San Diego, CA USA, 6-10 Oct. 1996, pp. 270-277.

[8] W. Limei and G. Qingding, “Sensorless control of permanent magnet linear synchronous motor based on nonlinear observer” *In Proceedings of the 8th IEEE International Workshop on Advanced Motion Control,* 2004. AMC'04, 25-28 March 2004. pp. 619-622.

[9] V. Ostović, *Dynamics of Saturated Electric Machines*. Springer-Verlag. New York. 1989.

[10] J. Holtz and J. Quan, “Sensorless vector control of induction motors at very low speed using a nonlinear inverter model and parameter identification” *IEEE Transactions on Industry Applications*, Vol. 38, No. 4, July-Aug. 2002, pp. 1087-1095.