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Sensorless position control of surface permanent magnet linear synchronous motors

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Abstract: In this paper, a novel sensorless position control for a surface permanent magnet linear synchronous motor (SPMLSM) is presented. The position and speed of the SPMLSM drive is obtained through a closed loop observer by only measuring phase voltages and currents. Estimation of speed is done using difference between estimates of the current derivatives in the dq frame, which calculated two different ways: first using a high-gain observer, and then using the motor model. Estimation of the mover position is done through integrating the estimation of speed. The proposed scheme works in a closed loop fashion. It enhances the allowable initial position error; can be used without any physical modification; does not rely on motor saliency and requires no knowledge of the load. Results from numerical simulations and practical implementation are presented to validate the proposed schemes.

Introduction

Recently the PMLSMs are increasingly utilized in industrial automation, transportation, and domestic appliances due to its compact structure, reduced size, low maintenance cost. The PMLSMs are gradually substituting linear drive systems which use a combination of rotary motors and lead-screws. To achieve high dynamics and stable performance, linear position sensors are required for the servo loop feedback. However, linear position sensors account for a large proportion of the total system cost. Furthermore, most linear position sensors have problems of difficult installation, low reliability, and are sensitive to alien surroundings. The reduction in mechanical robustness and cost of sensors makes elimination of these devices very desirable.

Consequently, position sensor elimination schemes have recently received wide attention. The position sensor elimination schemes have been successfully implemented for the interior-permanent-magnet motor drives [1, 2]. In these schemes, the back EMF of the motor is integrated in order to estimate the rotor position. The rotor position can also be estimated using the terminal voltage and the current through the motor phases [3, 4]. Using the advanced observers to estimate the rotor position is a recent approach discussed in the literature [5]. Extended Kalman filter (EKF) is well-known to be used to estimate position and speed. However, convergence can not be guaranteed.

This paper investigates the characteristics of an SPMLSM, estimates the magnetic pole position and mover speed by detecting the terminal voltage and current. The observer is developed from the *dq* model of the motor. Estimation of speed is done using differences between estimates of the current derivatives in the *dq* frame. High-gain observer is used to reduce the effect of the disturbance.

Position and speed detection algorithm

Mathematic model of the SPMLSM

The SPMLSM, a linear guide and an optical scale are mounted on an anti-shock table. In this work, the following assumptions are made regarding the SPMLSM:

(1)The induced electromotive force is sinusoidal; (2)Magnetic saturation, magnetic hysteresis and erratic current are neglected; (3)Primary windings are star connected and symmetrical. Number of turns in each winding is equal. Resistance of each winding is equal. And three armature windings are set at 120° to each other; (4)Surfaces of primary and secondary are both smooth.

The voltage phase-variable equation of a SPMLSM in stator-fixed reference frame (*a*, *b*, *c*) is as follows,

$$\begin{cases} u_a = Ri_a + Lpi_a - \dfrac{\pi}{\tau} v\psi_f \sin\theta \\ u_b = Ri_b + Lpi_b - \dfrac{\pi}{\tau} v\psi_f \sin(\theta - \dfrac{2\pi}{3}) \\ u_c = Ri_c + Lpi_c - \dfrac{\pi}{\tau} v\psi_f \sin(\theta + \dfrac{2\pi}{3}) \end{cases} \tag{1}$$

where u_a, u_b, u_c are voltage of three phase windings respectively. i_a, i_b, i_c are current of three phase windings respectively. R, L, τ are the phase resistance, the synchronous inductance, the pole pitch respectively. ψ_f is the amplitude of the flux linkage established in the phase windings, by the permanent magnet. θ and v is the position and speed of the motor respectively. p is the differential operator, $p=d/dt$.

Structure of observer

The underlying steps in the proposed scheme are: (1) Measure the motor currents and voltages; (2) Transform these variables to the dq rotor frame of reference using $\hat{\theta}$, the estimate of θ; (3) Calculate the derivatives of each of the currents $\hat{i}_q$ and $\hat{i}_q$, two different ways; (3) Use the error between the current derivatives to drive the observer.

Fig. 2 gives an overview of the proposed scheme. The details of the scheme follow.

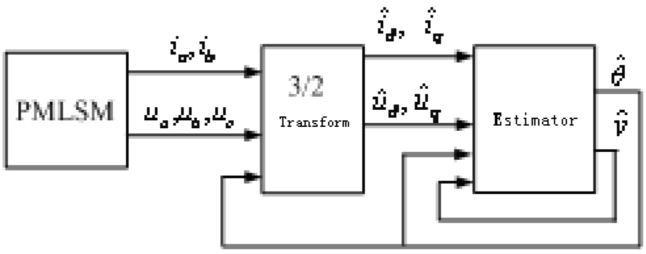

Fig. 1 Overview of the estimation algorithm

Firstly, voltage model of SPMLSM shown as (1) should be transformed to the *dq* frame. If the motor position θ is known, the following matrix will be used:

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{2}$$

where, f represents either a voltage or a current.

Since we are developing a sensorless scheme, θ is unknown, we use its estimate $\hat{\theta}$. This modifies (2) to:

$$\begin{bmatrix} \hat{f}_d \\ \hat{f}_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\hat{\theta} & \cos(\hat{\theta}-2\pi/3) & \cos(\hat{\theta}+2\pi/3) \\ -\sin\hat{\theta} & -\sin(\hat{\theta}-2\pi/3) & -\sin(\hat{\theta}+2\pi/3) \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{3}$$

Carrying out the transformation, (1) and (2) yield:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R+Lp & -L\frac{\pi v}{\tau} \\ L\frac{\pi v}{\tau} & R+Lp \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{\pi v}{\tau}\psi_f \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{4}$$

while, (1) and (3) result in:

$$\begin{bmatrix} \hat{u}_d \\ \hat{u}_q \end{bmatrix} = \begin{bmatrix} R+Lp & -L\frac{\pi \hat{v}}{\tau} \\ L\frac{\pi \hat{v}}{\tau} & R+Lp \end{bmatrix} \cdot \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} + \frac{\pi v}{\tau}\psi_f \begin{bmatrix} -\sin\Delta\theta \\ \cos\Delta\theta \end{bmatrix} \tag{5}$$

where $\hat{v}$ is speed estimate, and $\Delta\theta = \theta - \hat{\theta}$

Rearranging (5), we get

$$p\hat{i}_q = \frac{1}{L}\hat{u}_q - \begin{bmatrix} L\frac{\pi\hat{v}}{\tau} & R \end{bmatrix} \cdot \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} - \frac{\pi v}{\tau}\psi_f \cos\Delta\theta \tag{6}$$

where $p\hat{i}_q$ can be calculated by finding the derivative of the signal known to us: $\hat{i}_q$. High-gain observers will be used to find the derivative.

Another way will be used to calculate the derivative. We define a new set of variables, replicating (6) but assuming $\Delta\theta$=0 and $\hat{v} = v$:

$$p\hat{i}_{qm} = \frac{1}{L}\hat{u}_q \begin{bmatrix} L\frac{\pi\hat{v}}{\tau} & R \end{bmatrix} \cdot \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} - \frac{\pi\hat{v}}{\tau}\psi_f \tag{7}$$

Further defining: $\Delta p\hat{i}_q = p\hat{i}_q - p\hat{i}_{qm}$

(6) - (7) yields the error in current derivative:

$$\Delta p\hat{i}_q = \frac{\pi\psi_f}{\tau L}(-v\cos\Delta\theta + \hat{v}) \tag{8}$$

Assuming that $\Delta\theta$ is small. Thus,

$$\Delta p\hat{i}_q = \frac{\pi\psi_f}{\tau L}\Delta v \tag{9}$$

where $\Delta v = v - \hat{v}$. Rearranging (9), we get: $\Delta v = -\frac{\tau L}{\pi\psi_f}\Delta p\hat{i}_q$

Substituting the definition of Δv from the above equation, it can be re-written as:

$$v = \hat{v} - \frac{\tau L}{\pi\psi_f}\Delta p\hat{i}_q \tag{10}$$

For the purpose of implementation, (10) can be expressed as:

$$\hat{v}_{new} = \hat{v} - \frac{\tau L}{\pi\psi_f}\Delta p\hat{i}_q \tag{11}$$

(11) is a high-gain observer. Divides each side of (11) by the sample time T. we obtain:

$$\frac{\hat{v}_{new} - \hat{v}}{T} = -\frac{\tau L}{T\pi\psi_f}\Delta p\hat{i}_q = h\Delta p\hat{i}_q \tag{12}$$

Because T is small, the left-hand side of (12) can be regarded as the derivative of $\hat{v}$. Thus,

$$\dot{\hat{v}} = h\Delta p\hat{i}_q \tag{13}$$

where h is the observer gain. The typical sampling frequency is 10kHz~20kHz. Therefore the gain h is very high. This high gain observer ensures that the effect of the disturbance can be neglected.

The estimation of position $\hat{\theta}_{new}$ can be calculated by integrating the speed estimation $\hat{v}_{new}$.

Fig. 2 shows the above algorithm graphically. Fig. 3 gives the speed and position estimate results. Fig. 4 gives their errors.

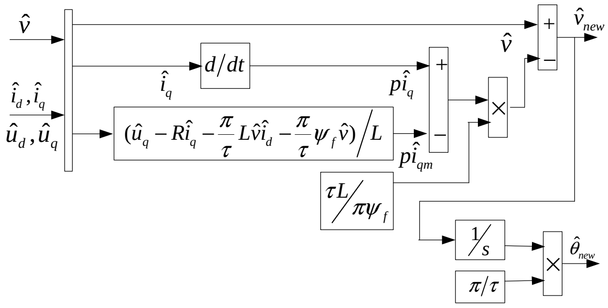

Fig. 2 Details of the proposed scheme

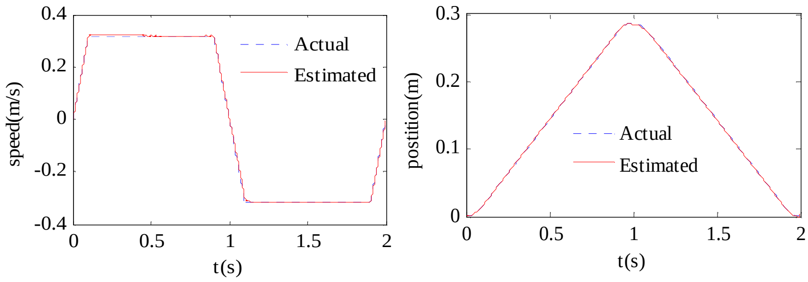

Fig. 3 Speed and position estimated curves

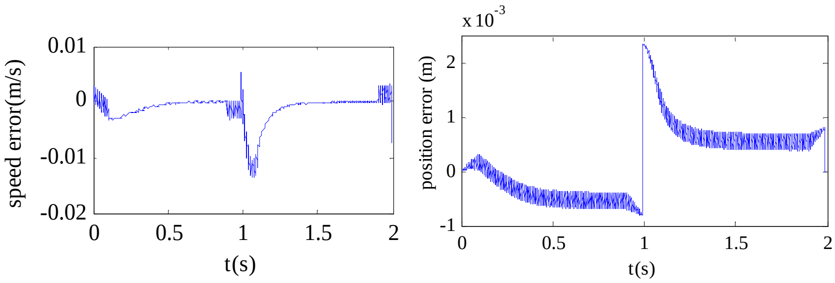

Fig. 4 Errors of speed and position

Experimental results

The experimental results are obtained using a surface PMLSM servo drive. A fixed point digital signal processor (DSP), TM320F2812, is used to run the vector control algorithm. The control and estimation period is 60 μs. The PWM switching frequency for insulated gate bipolar transistors is 16 kHz. The DSP also runs the speed and position estimation algorithm.

Fig. 5 and Fig. 6 shows the speed curve when the motor is running at 500mm/s and 50mm/s respectively.

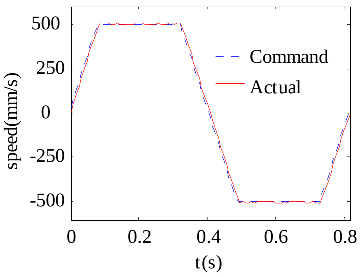

Fig. 5 High speed curve

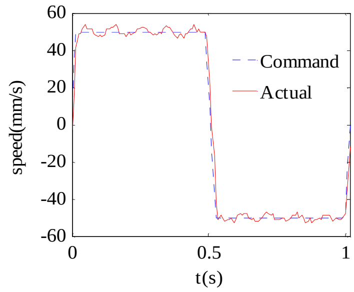

Fig. 6 Low speed curve

Conclusion

In this paper a simple algorithm for detecting speed and position based on high-gain observer is proposed. It can estimate the magnetic pole position and mover speed by detecting the voltage and current of permanent magnet linear synchronous motor. It is demonstrated that the high-gain observer provides reliable position information for a controlled force, closed loop start up and sound performance of low speed running at 50 mm/s.

The presented work demonstrates that the measured terminal currents and voltages, together with the machine parameters, can be used to obtain speed and position in real-time. The method can be employed in drive systems with SPMLSM, or any type of LSM (linear synchronous motor), that requires a controlled force start up under high load using the rated current, which gets better performances at low running speed.

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