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Initial mover position estimation of permanent magnet linear synchronous motor with signal injection method

Abstract. *This paper proposes a useful method to estimate the initial mover position of a surface-mounted permanent magnet linear synchronous motor (SPMLSM). The estimation is performed by saliency effect and nonlinear magnetization characteristics of stator core. Two available methods of pulse voltage injection and high-frequency injection are analyzed in detail, and then a relatively simple approach in signal processing is proposed. By the measurement of a SPMLSM prototype, the high-frequency injection method is proved more accurate and reliable than pulse-voltage injection method in estimation of the initial mover position.*

Streszczenie. *W artykule zaproponowano metodę określania położenia element ruchomego liniowego silnika synchronicznego z magnesami stałymi SPMLSM. W obliczeniach wykorzystano nieliniową charakterystykę namagnesowania rdzenia stojana. Analizowano dwie metody wstrzykiwania napięcia impulsowego i wysokoczęstotliwościowego. (**Określanie początkowej pozycji elementu ruchomego w silniku liniowym synchronicznym metodą wstrzykiwania sygnału**)*

Keywords: Permanent magnet linear motors; initial mover position; saliency effect; signal injection method
Słowa kluczowe: liniowy silnik synchroniczny, pozycja element ruchomego

Introduction

The starting performance of permanent magnet linear synchronous motor (PMLSM) closely depends on initial mover position in the high-performance servo control system. Since the initial mover position can't be obtained by incremental grating when system is powered on, sometime the specified voltage vector is adopted to locate the mover. The disadvantage is that the motor will be moving during the location. To high performance servo systems, the intial moving is forbidden, therefore the initial mover position should be estimated in stationary state.

In PMSM, *d*-axis inductance is not equal to *q*-axis inductance due to the saliency effects, and the inductance changes with the variation of mover position. The rate of current change depends on winding inductance, so the mover position can be deduced from the rate of winding current [1]. For rotating PMSM, several mover position estimation methods have been proposed based on inductance variation. According to injection signal, they can be classified to pulse-voltage method and high-frequency injection method. Nakashima *et al.* estimated the initial rotor position of SPMSM with pulse-voltage method [2]. Wang *et al*. calculated the inductance matrix in the basis of the pulse voltage method，then got the initial rotor position [3]. To high-frequency injection, it has rotating high-frequency injection and fluctuating high-frequency injection [4-13]. Its key problem is high-frequency current signal processing. Therefore, Shinnaka designed a phase-locked loop [14], and Foo *et al.* used a sliding observer in high-frequency signal injection [15]. These methods have good dynamic performance, so they are suitable for sensorless control system, but they are too complex to estimate the initial mover position in servo system which used incremental grating or incremental encoder as position sensor. A simple approach of signal processing is required in this application.

This paper investigates the initial mover position estimation methods for SPMLSM by pulse-voltage method and high-frequency injection method, and adopt a relatively simple approach in signal processing. Though the experimental results of the two methods, their accuracy and stability are discussed.

Estimation methods of Initial mover position

1) Pulse-voltage method

Due to the static friction and mechanical inertia, the mover of PMLSM can't move with a very short time voltage vector injection into the stator winding. In this condition, the stator winding can be taken as a one-order circuit composed by a single resistor and inductor, so the current step response can be expressed as follow:

$$i(t) = \frac{U_{\mathrm{M}}}{R_s}\left(1-e^{-t/\tau}\right)\varepsilon(t)\Bigg|_{\tau=\frac{L}{R_{\mathrm{s}}}} \tag{1}$$

where U_{M} – magnitude of pulse voltage vector, R_{s} – stator winding resistance, L – inductance, τ– time constant.

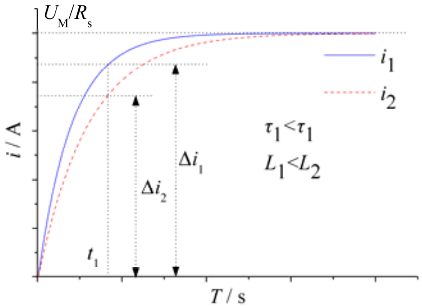

Fig.1 Current response under step voltage excitation

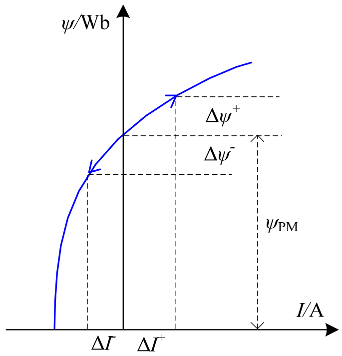

Fig. 2 Magnetization curve of stator core

The current response with step voltage excitation is shown in Fig 1. When the pulse voltage vector is injected for a certain time, it achieves larger current with smaller inductance. Base on saturation saliency effect, the *d-axis* inductance is smaller than the *q*-axis inductance in SPMLSM. With injecting a series of voltage vectors to stator winding, and the phase of voltage vector has the highest current amplitude in the position of *d*-axis, that is to say, the position of *d*-axis can be obtained. Since the *d*-axis has N pole and S pole, the position of N pole is normally taken as the mover position. The nonlinear magnetization characteristics of stator core is used to to distinguish the N pole and S pole (see Fig. 2). ΔI^{+} is bigger than ΔI^{-} when $\Delta \Psi^{+}$ is equal to $\Delta \Psi^{-}$. That is to say, the amplitude of current along magnetic field direction is bigger than the current against magnetic field direction. N pole is along the direction of the magnetic field, and S pole is against the direction of the magnetic field. In summary, the phase of voltage vector which has the highest current amplitude is the position of N pole (mover position).

2) High frequency method

In the *d-q* coordinates, the equation of SPMLSM is expressed as follows:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + p \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \frac{\pi v}{\tau} \begin{bmatrix} -\psi_q \\ \psi_d \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \psi_{PM} \\ 0 \end{bmatrix} \tag{3}$$

where u_d – *d*-axis voltage, u_q – *q*-axis voltage, i_d – *d*-axis current, i_q – *q*-axis current, L_d – *d*-axis inductance, L_q – *q*-axis inductance, ψ_{PM} – permanent magnet flux, τ –pole pitch, v – mover velocity.

The frequency of the injected signal is much higher than the electrical angular frequency of SPMLSM. Then, its model can be simplified to one-order resistor-inductor (*RL*) circuit under high-frequency injection condition. Moreover, the effect of resistance is far less than the inductance, so the high-frequency voltage equation of SPMLSM can be expressed as follow:

$$\begin{bmatrix} u_{di} \\ u_{qi} \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} p \begin{bmatrix} i_{di} \\ i_{qi} \end{bmatrix} \tag{4}$$

The current response is obtained.

$$p \begin{bmatrix} i_{di} \\ i_{qi} \end{bmatrix} = \begin{bmatrix} L_d^{-1} & 0 \\ 0 & L_q^{-1} \end{bmatrix} \begin{bmatrix} u_{di} \\ u_{qi} \end{bmatrix} \tag{5}$$

Define the error angle $\Delta\theta$ of mover as the difference between actual mover position θ_r and estimated mover position θ_{r}^{*}. $\Delta\theta$ can be expressed as (6):

$$\Delta\theta = \theta_{\mathrm{r}} - \theta_{\mathrm{r}}^{*} \tag{6}$$

In the *d-q* coordinates, the differential eguation of current response in stator can be expressed as (7):

$$p \begin{bmatrix} i_{di}^{*} \\ i_{qi}^{*} \end{bmatrix} = \begin{bmatrix} \cos\Delta\theta & -\sin\Delta\theta \\ \sin\Delta\theta & \cos\Delta\theta \end{bmatrix} \begin{bmatrix} L_d^{-1} & 0 \\ 0 & L_q^{-1} \end{bmatrix} \begin{bmatrix} \cos\Delta\theta & \sin\Delta\theta \\ -\sin\Delta\theta & \cos\Delta\theta \end{bmatrix} \begin{bmatrix} u_{di}^{*} \\ u_{qi}^{*} \end{bmatrix} \tag{7}$$

and then current response can be calculated:

$$\begin{bmatrix} i_{di}^{*} \\ i_{qi}^{*} \end{bmatrix} = \begin{bmatrix} \int \left(\frac{1}{L^2 - (\Delta L)^2} \left(u_{di}^{*} \left(L + \Delta L \cos(2\Delta\theta) \right) + u_{qi}^{*} \Delta L \sin(2\Delta\theta) \right) \right) dt \\ \int \left(\frac{1}{L^2 - (\Delta L)^2} \left(u_{di}^{*} \Delta L \sin(2\Delta\theta) + u_{qi}^{*} \left(L - \Delta L \cos(2\Delta\theta) \right) \right) \right) dt \end{bmatrix} \tag{8}$$

where:

$$L = \frac{L_d + L_q}{2}, \quad \Delta L = \frac{L_q - L_d}{2} \tag{9}$$

In this method, the high-frequency sinusoidal voltage signal only injects into *d*-axis, it can be expressed as:

$$\begin{bmatrix} u_{di}^{*} \\ u_{qi}^{*} \end{bmatrix} = \begin{bmatrix} U_i \cos\omega_i t \\ 0 \end{bmatrix} \tag{10}$$

Substituting (10) into (8), the high-frequency current signal can be simplified as:

$$\begin{bmatrix} i_{di}^{*} \\ i_{qi}^{*} \end{bmatrix} = \begin{bmatrix} \frac{U_i \sin(\omega_i t)}{\omega_i \left(L^2 - (\Delta L)^2 \right)} \left(L + \Delta L \cos(2\Delta\theta) \right) \\ \frac{U_i \sin(\omega_i t)}{\omega_i \left(L^2 - (\Delta L)^2 \right)} \left(\Delta L \sin(2\Delta\theta) \right) \end{bmatrix} \tag{11}$$

According to (11), the current response under high-frequency excitation condition is shown in Fig.3. The variation of $\Delta\theta$ is from 0 to 2π. Apparently, the rate of high-frequency current change depends on the value of ΔL. Although SPMLSM is non-salient pole motor, it can show saturation saliency effect under the excitation of high-frequency voltage signal.

By comparing with the amplitudes of high-frequency current signals, initial mover position can be determined. As shown in Fig.3 (a), *d*-axis high-frequency current i_{di}^{*} has two maximum values when $\Delta\theta$ changes from 0 to 2π, and i_{qi}^{*} has four maximum values in Fig.3 (b). Initial mover position exists in the location of these maximum values, so it requires fewer judgment operations when i_{di}^{*} is used as estimation parameter. When the i_{di}^{*} achieves the maximum, $\Delta\theta$ is 0 or π, and then corresponding mover position is θ_{r}^{*} or $\theta_{\mathrm{r}}^{*} + \pi$ from (6). In addition, it also needs to judge polarity by nonlinear magnetization characteristics of stator core. After that, the position of N pole is obtained, which is the mover position of SPMLSM.

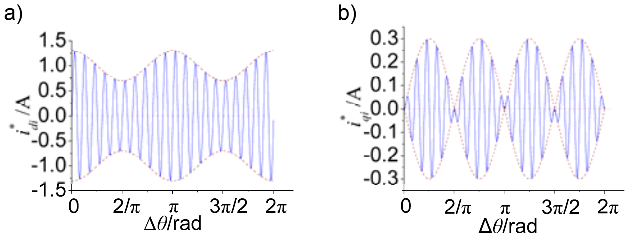

Fig. 3 High-frequency current response

Signal processing

Fig.4 shows the process of position estimation with pulse voltage method. The estimation method can be divided into two processes:

In the first process, eight pulse-voltage vectors are injected between 0 and 2π in the order 1 → 2 → 3 → 4 → 5 → 6 → 7 → 8 by the angle step π/4, and then eight corresponding current responses can be obtained .From these current responses, the maxmium value in the *d*-axis current is found. For example, If the *d*-axis current achieves the maxmium with “3” voltage vector, the phase of “3” voltage vector is set as one boundary of mover position interval. The phase of “2” voltage vector is set as another boundary if *d*-axis current under excitation of “2” voltage vector is larger than that of “4” voltage vector. That is to say, the mover position range is in (2, 3).

In the second process, the range (2, 3) is divided into four sub-intervals. Pulse-voltage vectors are injected in the order 9 → 10 → 11 → 12 → 13 with the step of π/16. Two particular voltage vectors can be found respectively according to the largest i_{di}^{*} and the second largest i_{di}^{*}. Therefore, the mover position is fixed in the phase range of these two voltage vectors. The midpoint of this interval is mover inital position, so the estimation error is smaller than ±π/16 electrical degree.

Theoretically, the range of mover position can be infinitely subdivided, so that the estimation error can be decreased as possible. But SPMLSM is non-salient pole motor, the difference between L_d and L_q is small, so the rate of current change is getting smaller along with the interval is subdivided into a smaller range. Since the small change is hard to be detected by current sensor, suitable subdivision should be selected according to the motor type.

The current change is susceptible to be affected by noise if it is small. In order to avoid the interference of sampling noise, the amplitude or injection time of voltage vectors need to be enlarged, especially such as “9” to “13” voltage vectors as shown in Fig.4. Since the phase sectors are close to the actual mover position in the second process, electromagnetic thrust decreases, so the stationary state of PMLSM is not prone to be disturbed.

The voltage vectors are injected clockwise continuously, positive electromagnetic thrust is produced in 1 → 2 → 3 → 4 voltage vectors, and negative electromagnetic thrust is produced in 5 → 6 → 7 → 8 voltage vectors. If the stationary state of SPMLSM is disturbed, the injection order can be changed into 1 → 5 → 2→ 6 → 3 → 7 → 4 → 8 to avoid the disturbance. The signal processing is relatively simple.

The process of high-frequency signal injection method is similar to that of pulse voltage method, main differences are the injection source is high-frequency sinusoidal signal and the injected direction is *d*-axis.

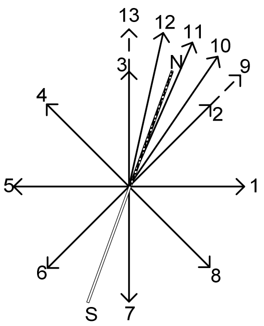

Fig. 4 Voltage vectors

Experiment and results

1) Platform of Linear Motor

The experiment platform of SPMLSM is shown in Fig.5. To SPMLSM prototype, the stator resistance per phase is 2.23Ω, the *d*-axis inductance is 30mH, *and q*-axis inductance is 39mH. In the control units, TI floating-point processor TMS320F28335 is adopted. During the injection, pulse voltage injection time is 0.002s with carrier frequency 5000Hz, and pulse voltage vector is applied to 10 carrier cycles. The amplitudes of “1-8” voltage vectors are set to 21.6V, and 27.7V for “9-13” voltage vectors. When the frequency of injected signal is 150Hz, this SPMLSM has a more obvious saturation saliency effects. The measured amplitude of injected signal was 13.875V and 24.942V for the subdivision stage.

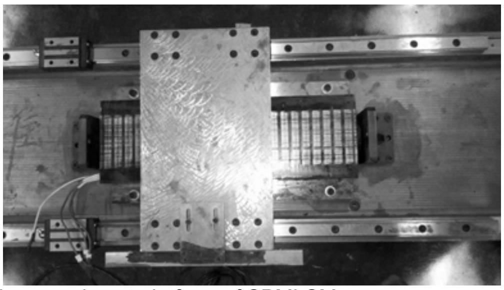
Fig.5 The experiment platform of SPMLSM

2) Result of pulse-voltage method

The measured *d*-axis current of pulse-voltage method is shown in Fig.6. The amplitudes of thirteen voltage vectors are shown in table 1. In the measurement, there should be enough time for the zero vectors between two injection operations, then the current can be restored to zero. According to the first eight results, the interval of N pole was (1, 2), and the corresponding radian interval is (0 rad, 0.785 rad). After the interval is divided into four sub-intervals, mover position can be determined at (9, 10) according to the results from “9” to “13”. That is to say, the corresponding radian interval is (0 rad, 0.196 rad). Due to the midpoint of the interval is taken as the estimated initial position of mover, the estimation error is 0.0982 rad since the actual reference initial position of mover is 0 rad.

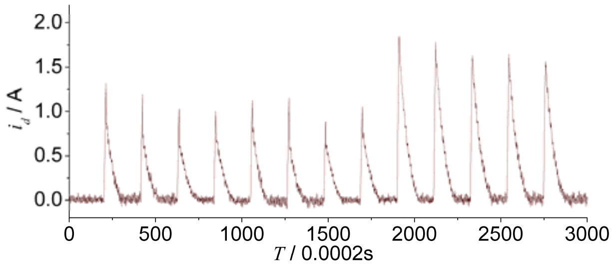

Fig. 6 Measured current of *d* axis

Table 1. Measured *d*-axis current of pulse-voltage method

NO.	i_d^* /A	NO.	i_d^* /A
1	1.321319	8	1.056435
2	1.200067	9	1.82066
3	1.030856	10	1.782315
4	1.001639	11	1.637254
5	1.12967	12	1.653165
6	1.160216	13	1.567967
7	0.8887385		

3) Result of high-frequency injection method

As the SPMLSM saliency effects is not very obvious，the amplitude changes of *d*-axis high-frequency current is also small, therefore the samll difference is susceptible to be affected by the noise signal. In order to avoid the influence of noise, i_{di}^* needs to be filtered with a 4-order Butterworth band-pass filter, which sampling frequency is 5000Hz and passband is (100Hz, 200Hz).

Table 2. *D*-axis current of high-frequency signal injection method

NO.	i_d^* /A	NO.	i_d^* /A
1	0.3287990	8	0.3758562
2	0.3566591	9	0.7155007
3	0.4062358	10	0.7162948
4	0.3753890	11	0.7090173
5	0.3290473	12	0.6897156
6	0.3560824	13	0.6643178
7	0.4075959		

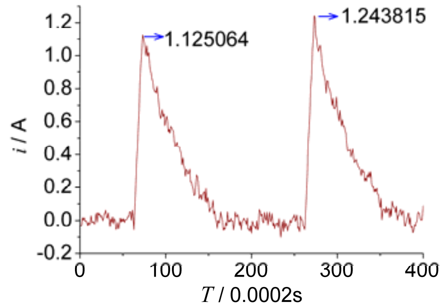

Fig.7 Measured *d*-axis current response in polarity judgment

The measured high-frequency current responses are shown in table 2. According to the first eight results, the interval of N pole or S pole is (7, 8), and the corresponding radian interval is (4.712 rad，5.498 rad). After the interval is divided into four sub-intervals, the mover position can be determined at (9, 10) according to the results from “9” to “13”, which corresponds to the radian interval (4.712 rad，4.909 rad). The midpoint of this interval is 4.811 rad, which is the position of N or S pole. The polarity is determined by the nonlinear magnetization characteristics of stator core, shown in Fig.7. 4.811 rad and 4.811-π rad is used in polarity judgment, and the estimation error is -0.098 rad finally. The estimation results with different mover reference positions are shown in Fig. 8. The θ_r is the actual reference position of mover, and θ_r^* is the estimation position of mover. Root mean square error of prediction (RMSEP) for the estimation results is 0.139 rad.

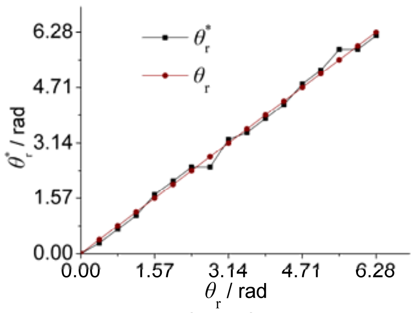

Fig.8 The estimation results of high-frequency signal injection

4) Analysis of results

When the pulse-voltage method is used in the detection of initial position the amplitude of current response corresponding to “9-13” voltage vectors in the sub-interval should be shown a decreasing trend because the acutal reference initial mover position is 0 rad. However, the measurement shows the current amplitude corresponding to the “12” voltage vector is greater than the current corresponded to “11” voltage vector. It indicates that the sampling error can’t be neglected in pulse-voltage method. Furthermore, there are also several polarity errors with the final position detected is the position of S pole instead of N pole. It can be concluded that the sampling results are easy to be affected by noise if current response are very short in the pulse-voltage method, and the amplitude of current is sampled once time. That is to say, it is necessary to repeate sampling operations several times when pulse-voltage method is used to detected mover initial position. Since thirteen voltage vectors need to be injected repeatedly, the complexity and time spent are also increased.

The current response is a sinusoidal signal under high-frequency voltage excitation, so average current amplitude of more than one cycle can be sampled. Compared with the former pulse-voltage method, the advantage of this method is less susceptible to be affected by sampling error, therefore the results have the characters of high stability and accuracy. However, the polarity judgment also needs pulse-voltage method, so that the influence of sampling error in this step also can’t be ignored. Two voltage vectors in opposite phase are used to judge the polarity. Since only two voltage vectors are used, it is easy to judge which result is correct. During the process of judgment, the amplitudes of current respond increases along with the amplitude of the voltage vector increasing, and then, the influence of sampling error can be reduced. Additionally, angle between mover magnetomotive force and stator magnetomotive force is 0 or π, so electromagnetic thrust is weak, the stationary state of SPMLSM don’t be disturbed even increasing the amplitude of voltage vector.

Conclusions

To the estimation of initial mover position, pulse-voltage method and high-frequency signal method can be used. Both two depend on inductance variation. By comparing, pulse-voltage method is easy to be realized and spends less time, but it is susceptible to be affected by sampling error, especially when the saliency effects of SPMLSM is obscure. To high-frequency signal injection method, average current amplitude is used as a judgment condition, and Butterworth IIR is used to filter the noise in current signal, so that the results have the characters of higher stability and higher accuracy.

Both pulse-voltage method and high-frequency signal injection method are based on the variation between *d*-axis inductance and *q*-axis inductance. Due to the variation is faint in SMPMLSM. The accuracy of mover position estimation still can’t meet the high-precision CNC machine tool requirements although the high-frequency signal injection method increases the detection accuracy and stability by proposed signal processing mehtod. But it is enough to detect the intial mover position for helping the starting of the SPMLSM in long-stroke linear logistics system.

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