Simulation of Sensorless Control for FSPMLM with high-frequency signal injection

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Abstract. This paper probes into a sensorless control method of flux-switching permanent linear magnet (FSPMLM) with high-frequency signal injection, and analyses the FSPMLM structure through salient pole verification. Specifically, a high frequency sinusoidal voltage signal was superimposed into the estimated d-axis, and the mover position was demodulated after the regulation of q-axis current, which is relative to error angle. Ultimately, the exact mover position and speed were obtained. To solve the starting problem of the FSPMLM, improved magnetic pole identification was performed based on space vector pulse width modulation for an arbitrary initial position. Through the simulation of the FSPMLM and the control system, it is confirmed that the proposed approach is of high accuracy and effectiveness.

1. Introduction

The flux-switching permanent magnet linear machine (FSPMLM), featured by simple secondary structure, high thrust density and minor cogging force, has become a desirable direct-drive application in feeding system of the machine tool in demand of high force capability[1-2]. In order to synchronize the phase excitation pulse to the mover position, the high performance speed or position control requires an accurate measurement of mover shaft position and velocity. This calls for speed or position sensors, e.g. a grating line displacement transducer, to be attached to the motor shaft. However, these sensors pose several disadvantages in most applications, namely low reliability, noise-proneness, high-cost, heavy weight and complexity of the drive system. These difficulties can be overcome by the drive system of position and velocity sensorless control of flux-switching permanent linear (PMSM).

Due to the lack of research on the sensorless control of FSPMLM, it is necessary to study the sensorless control for PMSM considering the consistency of the mathematic model of FSPMLM and PMSM. For the past decade, efforts have been made for rotor position estimation in sensorless control of PMSM. Broadly speaking, there are two types of sensorless position estimation plans for PMSM. One is based on the back electromotive force (EMF) voltage estimation [3-7], including voltage model, state observer, or Kalman filters. This approach works well in the middle and high-speed regions. The amplitude of the back EMF is proportional to the rotor speed, but it fails at low or at zero speed. The motor back EMF value is so small that rotor-flux-estimation results are highly sensitive to stator resistance variations. Low-speed operation may be at stake with some simple measurement noises. The other type of sensorless position estimation plans are grounded on magnetic saliency [8-12]. The basic idea of these plans is to inject extra voltage or current signals into motor and detect the rotor position.
with the corresponding signals. This type of plans can detect inductance using voltage signals within a short time. The strength of these plans lies in the insensitivity to parameter variation or measurement noises. For example, the position can be estimated even at standstill and low speeds. However, the above estimation methods for initial rotor position only focus on the axis of the magnets, failing to obtain the magnetic polarity regarding sensorless control of PMSM at zero speed. Whereas the conventional method for (N-S) pole is determined based on the magnetic saturation, the commonly method is to inject pilot voltages before ascertaining pole polarity based on the corresponding current.

In light of the above, this paper probes into a sensorless control method of flux-switching permanent linear magnet (FSPMLM) with high-frequency signal injection, and analyses the FSPMLM structure through salient pole verification. Specifically, a high frequency sinusoidal voltage signal was superimposed into the estimated d-axis, and the mover position was demodulated after the regulation of q-axis current, which is relative to error angle. Ultimately, the exact mover position and speed were obtained. To solve the starting problem of the FSPMLM, improved magnetic pole identification was performed based on space vector pulse width modulation for an arbitrary initial position. Through the simulation of the FSPMLM and the control system, it is confirmed that the proposed approach is of high accuracy and effectiveness.

**2. Verify the salient pole of FSPMLM**

The basic idea of peak tracking scheme is to inject high frequency voltage into the engine and detect the spatial position of the driver by measuring the inherent spatial output of the engine. Therefore, this paper first verifies the advantages of FSPMLM. Fig. 1 shows the configuration and cross-section of a long main FSPMLM with a convex actuator. The recommended stator of machine tool is pure magnetic conductor without induction or permanent magnet. The transmission device consists of hinges, permanent magnets and iron cores.

![Figure 1. Structured and cross-section of double-sides FSPMLM.](image)

Three-phase mutual perception can be expressed as (1) and (2). However, due to the terminal effect, there is a constant value shift, whether it is the self-inductance of stage B or the interaction between stage A and stage C.

\[
\begin{align*}
L_{aa} &= L_0 + L_a \cos(2\pi x / \tau) \\
L_{bb} &= L_0 + L_a \cos(2\pi x / \tau + 2\pi / 3) + L_1 \\
L_{cc} &= L_0 + L_a \cos(2\pi x / \tau - 2\pi / 3) \\
L_{ab} &= L_0 + L_a \cos(2\pi x / \tau) \\
L_{bc} &= L_0 + L_a \cos(2\pi x / \tau + 2\pi / 3) + L_1 \\
L_{ca} &= L_0 + L_a \cos(2\pi x / \tau - 2\pi / 3)
\end{align*}
\]

(1)

(2)

\(L_0\) and \(M_0\) are the fixed components of self-awareness and interaction respectively. \(L_1\) is the constant offset of self-inductance of phase B; \(M_1\) is the offset of the interaction between stage a and stage c; \(M_a\) and \(L_m\) are the magnitude of the fundamental component; \(\Delta\) is the relative displacement of the operator.

Using the famous Parker transform, the D-axis and Q-axis components of inductance are obtained by the following formula

\[L(d,q,0) = PL(a,b,c)P^{-1}\]

(3)
FEA results of the d and q axis inductances is shown as Figure 2, it can be seen that, so flux-switching permanent magnet linear machine (FSPMLM) with high-frequency signal injection on the basis of salient pole Verification is feasible.

![Figure 2. FEA results of the d and q axis inductances.](image)

2.1. Mathematical model of PMSM excited by high frequency voltage

In the high-frequency circuit, when the high-frequency voltage is stimulated, the chirp generator is regarded as a simple R-L load. Note that the signal injection frequency is quite high relative to the rotor speed. In high frequency circuits, cross coupling and reverse kinetic energy can be ignored. Since the actual location of the sub-operator traffic cannot be calculated, it is better to use only the estimated reference of the sub-operator instead of the actual reference. Therefore, the high frequency stress equation in the orientation coordinates of the estimation operator can be expressed as (4)

\[
\begin{bmatrix}
    V'_{dsh} \\
    V'_{qsh}
\end{bmatrix} = \begin{bmatrix}
    \Sigma z + \Delta z \cos 2\Delta \theta_m & \Delta z \cos 2\Delta \theta_m \\
    \Delta z \cos 2\Delta \theta_m & \Sigma z - \Delta z \cos 2\Delta \theta_m
\end{bmatrix} \begin{bmatrix}
    i'_{dsh} \\
    i'_{qsh}
\end{bmatrix}
\]

(4)

\(i'_{dsh}, i'_{qsh}, V'_{dsh}, V'_{qsh}\) is the high-frequency component of the current of the d-axis and q-axes, respectively. \(z'_{dsh}\) and \(z'_{qsh}\) is the high-frequency impedance of the d-axis and the q-axis respectively.

\[
\Delta \theta_m = \theta_m - \hat{\theta}_m
\]

(5)

\(\Sigma z\) and \(\Delta z\) is the difference and average value of high-frequency impedance of d-axis and q-axis:

\[
\Sigma z = (z'_{dsh} + z'_{qsh}) / 2 \\
\Delta z = (z'_{dsh} - z'_{qsh}) / 2
\]

In order to reduce torque ripple, the high frequency voltage signal is injected only into the D axis of the rotor reference system.

\[
\begin{bmatrix}
    v'_{dsh} \\
    v'_{qsh}
\end{bmatrix} = \begin{bmatrix}
    v_{HFI} \cos \omega_i t \\
    0
\end{bmatrix}
\]

(6)

The amplitude and frequency of the injected HV signal are \(v_{HFI}\) and \(\omega_i\), respectively.

Because high frequency induction is enough to exceed high frequency resistance. The description of high frequency current is based on (4)-(6).

\[
i'_{dsh} = \cos \omega_i t v_{HFI} (\Sigma L \Delta L \sin 2\Delta \theta_m)
\]

(7)

\[
i'_{qsh} = -\sin \omega_i t v_{HFI} (\Sigma L \Delta L \sin 2\Delta \theta_m)
\]

(8)

Based on this equation, the position of the mover is estimated by the q-axis high-frequency current.
When the estimated operator position is close to the actual operator position, the high frequency current of $q$-axis is almost zero.

Fig. 3 shows the framework of obtaining traditional local error signals based on high frequency voltage stimulation factors. In order to obtain errors from the (7) engine positions, filters of optical filter (BPF) and low availability filter (LPF) are used in signal processing.

If the position error $\Delta \theta_m$ of the sub-moving operator is small enough, the signal input to (7) can be roughly

$$e(\Delta \theta_m) = LPF\left[ \hat{i}_{qs} \sin \omega_s t \right]$$

$$\approx \frac{V_{HF} \Delta L}{2w_s L_{st} L_{qph}} \sin 2\Delta \theta_m = K_{err} \Delta \theta_m$$

(9)

As shown in fig. 3, if scaling integral control and divisor are used as the estimated value of the sub-operator position, the function of converting the actual sub-operator position to the estimated position can be expressed as follows

$$H(s) = \frac{k_{pu} K_{err} s + k_{pu} K_{err}}{s^2 + k_{pu} K_{err} s + k_{pu} K_{err}}$$

(10)

3. Pole Identification Based on Space Vector Pulse Width Modulation

When the magnetic pole is located at any initial position shown in Figure 4, we must first detect the chirp axis. It is usually realized by high frequency voltage injection, but the magnetic pole is unknown. Therefore, an extra process is needed to determine the magnetic polarity. As described below, this additional process is called polarity determination.

![Figure 4. Magnetic pole identification based on saturation effects.](image)

![Figure 5. Applied voltage vectors and mover position areas.](image)

![Figure 6. Magnetic pole identification](image)
Distinguishing N-pole from S-pole is the next step. Magnetic saturation effect will be used as a measurement method. After obtaining the initial position of the driven wheel, select the phase closest to the magnetic pole to apply the detection voltage. In this method, a voltage vector (VNS) needs to be applied for a period of time to saturate the operation. Figure 5 defines the space vector. When the direction of Q axis of actuator is known, it can easily calculate the phase coil closest to the magnetic pole of actuator. Then, a set of starting voltage vectors are applied to the phase coil closest to the moving secondary axis to detect the magnetic poles. The guidance voltage consists of positive drive and negative drive alternately. Both current amplitude and positive voltage are \( i_{B+} \); The amplitude of current is related to negative in voltage. It compares the magnitude of current pairs.

The proposed magnetic pole identification scheme is tested by single-point PMSM. Fig. 6 shows an experimental result. The amplitude of \( i_{B+} \) is 2.5A, and the amplitude of \( i_{B-} \) is 3A. The above driving voltage vector is based on SVPWM (U3 and U4).

Obviously, the north pole is the magnetic pole corresponding to i-b, so the position angle between \( \pi \) and \( 2\pi \).

4. The simulation experiment test

To test the accuracy of the above control method, the first step is to create a simulation test based on FSPMLM. The proposed sensorless control system is simulated in MATLAB Simulink. Figure. 7 shows the block diagram of FSPMLM sensorless drive system, including the recommended sensorless control algorithm.

![Figure 7. Back diagram of sensorless drive system of FSPMLM.](image)

Figure. 8 and 9 show the simulation results of high frequency control using low speed sensorless. Figure. 10 shows the sensorless performance at 2 MB/s speed command. Figure 9 shows that the commanded acceleration is 0 ~ 3m/s. Figure 8 and 9 show that the sensorless control algorithm can realize speed control without position or speed sensor, including zero speed.

![Figure 8. Actual and estimated mover position and its error in 2m/s.](image)

![Figure 9. Actual and estimated mover position and its error from 0~3m/s.](image)
5. Conclusion
The mathematic model of FSPMLM under high-frequency voltage injection helps to realize the mover position self-sensing for FSPMLM. The high-frequency injection method is able to achieve sensorless control and the saliency-tracking detection, and remains robust to external interference. In light of these, this paper presents an improved magnetic pole identification method based on SVPWM for initial mover position estimation. It is discovered that the N-S pole can be identified at any initial mover position through applying vector-controlled pilot voltages by SVPWM.

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