Rotor Position Recognition Technology of Permanent Magnet Linear Synchronous Motor Based on Sliding Mode Observer

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Abstract. Position sensorless control system of permanent magnet linear synchronous motor has some advantages: simple structure, easy maintenance, high efficiency, good speed performance, etc. This paper designed a position sensorless control system of permanent magnet linear synchronous motor based on sliding mode observer, namely taking advantage of a sensorless algorithm to estimate the pole position and speed. Firstly, the principle of sliding mode control and basic conditions which need to achieve are analyzed. And then, a sliding mode observer of the permanent magnet linear synchronous motor sensorless control system is designed. The related simulation model is built to study the effect of sliding mode observer for rotor position accuracy. The simulation model is implemented to build models of permanent magnet linear synchronous motor vector control system based on sliding mode observer and simulate the control performance of position sensorless control. In the last part, the feasibility of the design scheme is verified by analysis of simulation results.

1. Introduction
Permanent magnet linear synchronous motor exhibited the characteristics of high torque index, low loss and fast response. When compared with other high precision systems, it has great advantages. PMLSM has a wide range of applications, such as in the domain of CNC machine, high-speed transport, electromagnetic launch and hoisting system etc.

Position sensorless control system of permanent magnet linear synchronous motor not only has the characteristic of simple structure, easy maintenance, high efficiency, good speed control performance etc, but also has a few traits such as smaller, low cost, high reliability and can be used in some special place [1][2]. The paper proposed a sensorless vector control scheme of PMLSM based on sliding mode observer in order to solve the key issues of PMLSM position sensorless control system, and used Matlab/Simulink to build the basic module of the sensorless vector control system of PMLSM. Simulation results show that the proposed controller has stronger robustness and better anti-disturbance performance.

In the 1970s, international scholars began to study position sensorless for AC drive system. The most critical issue of sensorless control estimates the motor rotor position and speed, domestic and foreign scholars have done a lot of studies and research, proposed many representative positions and speed estimation method. The earliest sensorless methods are collectively called waveform detection method,
the feature point had been found by detecting waveform of physical quantities to identify rotor position. These physical quantities including current, voltage, flux, back-emf etc.

The back-emf zero-crossing detection method can be applied to permanent magnet DC motor position detection\cite{3}. The Back-emf integration method\cite{4} take advantage of the integration of non-conduction phase back-emf to obtain the signal of rotor position, when back-emf zero-crossing of off-phase, starting to integrate, and setting a threshold to cutoff integration signal. Freewheeling diode method that through detect diode of anti-parallel inverter bridge power switch tube conduction and off states to determine the rotor position. Rusong Wu proposed a method, the method utilized stator voltage and current get stator flux of real axis and imaginary axis in two-phase stationary stator coordinate, according to the two-phase flux arctangent value can get the position of the stator flux, and the rate of change of stator flux obtain motor speed.

The principle of the inductance measurement method\cite{5} is that the salient pole motor has salient-effects, the inductance of each phase winding will change with motor rotor position. The substance of observer is a state reconstruction, the principle is to reconstruct a system, which uses the original system can be directly measured variable (output vector and output vector) as the input signal, and make the output signal equal to the state of the original system under certain conditions. Existing observer including full-order state observer, reduced-order state observer, extended Kalman filter and sliding mode observer\cite{6,7,8}. In 1992, the scholars of department of electrical engineering of MIT have published a paper which adopted full-order state observer to build non-mechanical sensors permanent magnet synchronous motor control system. To meet the system's overall stability conditions, the full-order state observer must be an optimal linear estimation algorithm, considered the statistical characteristics of system model error and measurement noise, so can be applied to salient pole synchronous motor speed control system.

The JJ Slotine of MIT studied the nonlinear estimation problem of sliding mode observer, and made people begin to pay close attention to sliding mode observer. Because of sliding mode variable structure control system has the features of strength robustness against parameter disturbances, used sliding mode variable structure to substitute control loop of the state observer\cite{9}.

The main idea of model reference adaptive method (MRAS) is that will the equation of no unknown parameters as the reference model and the equation of estimated parameters as an adjustable model, both models have the same output. MRAS is used output errors of two models constituted suitable adaptive law to real-time adjust the parameters of the adjustable model, and achieved the adjustable model output tracking the reference model output.

Neural networks will be used for online identification and tracked of motor parameters, and conducted adaptive adjust for flux and speed controller\cite{11,12}. The non-linear neural network control combine with sliding mode control constituted two degrees of freedom control, the control strategy effectively solved the contradiction between track performance and robust performance of the linear servo system\cite{13}. The neural networks be combined with technology wavelet, and adopt the robust wavelet neural control overcame the slow learning deficiencies of simple neural network\cite{14}.

Under the framework of the vector control system, according to the similarity between linear motor and rotating motor and considering the particularity of permanent magnet linear synchronous motor, this paper constructs the block diagram of permanent magnet linear synchronous motor model in d-q axis synchronous rotating coordinate system. In this paper, the principle and characteristics of the sliding mode variable structure and the necessary conditions are analyzed. For the speed and position information required by the vector closed-loop control system, the sliding mode observer method in the sensorless algorithm is used to estimate. The method of estimating pole position and speed by sliding mode observer is analyzed in detail, and the vector control system of permanent magnet linear synchronous motor based on sliding mode observer is established. The system model of the sensorless permanent magnet linear synchronous motor control system is established using system simulation software. The control system is simulated to verify the feasibility of the control strategy.
2. Mathematical model of permanent magnet linear synchronous motor

In order to use the space vector to illustrate the problem better, we can utilize the current analytical method of the rotation motor, and will the magnetic field of permanent magnet linear synchronous motor as the space rotating magnetic field. In this rotating space, built the stationary α-β coordinate system and the rotating d-q coordinate system, figure 1 is shown the stator current vector of α-β and d-q coordinate system.

![Figure 1. Equivalent schematic of permanent magnet linear synchronous motor](image)

The permanent magnet of rotor is the salient structure and the stator has three-phase symmetrical armature winding, a-axis, b-axis, c-axis is the axis of the stator windings. Direct-axis d is the axis of the stator pole, counter-clockwise 90° is quadrature-axis q. θ is the angle of counterclockwise rotation that d-axis with respect to a-axis.

By the coordinate transformation, voltage equation and flux equation of PMLSM can be obtained in the d-q synchronous coordinate system:

\[
\begin{align*}
\frac{du_d}{dt} &= R_s i_d + \frac{dv_d}{dt} - \omega \psi_q \\
\frac{du_q}{dt} &= R_s i_q + \frac{dv_q}{dt} + \omega \psi_d
\end{align*}
\]

Where,

\[
\begin{align*}
\psi_d &= L_d i_d + \psi_f \\
\psi_q &= L_q i_q \\
\sin \delta &= \frac{\psi_q}{\psi_s}, \cos \delta = \frac{\psi_q}{\psi_s} \\
\psi_s &= \sqrt{(L_d i_d + \psi_f)^2 + (L_q i_q)^2}
\end{align*}
\]

Where, \(u_d, u_q, i_d, i_q, L_d, L_q, \psi_d, \psi_q\) is the voltage, current, inductance and flux of the d-q axis; \(R_s\) is stator resistance; \(\omega\) is electrical angular velocity, \(\omega = v \cdot \frac{\pi}{r}\); \(v\) is rotor line speed; \(\psi_f\) is d-axis flux component of the permanent magnet; \(r\) is polar pitch.

According to equation (3), (4) and power equation under the d-q coordinate system, the total power is:

\[
P_d = \frac{3}{2} (V_d i_d + V_q i_q) = \frac{3}{2} [(i_d^2 R_s + i_q^2 R_q) + (i_d \frac{\partial \psi_d}{\partial t} + i_q \frac{\partial \psi_q}{\partial t}) + P\omega (\psi_d i_q - \psi_q i_d)]
\]

The first term is the thermal dissipation of the motor; the second part is reactive power and the third term is the electromagnetic power of the motor, so there:

\[
P_v = F_m v = \frac{3}{2} P\omega (\psi_d i_q - \psi_q i_d)
\]

The electromagnetic thrust can be obtained by the formula (3), (4) and \(\omega = v \cdot \frac{\pi}{r}\),
\[ F_m = \frac{3\pi}{2\tau} [i_d\phi + (L_d - L_q)i_q^2] \]  

Where \( p \) is the number of pole pairs. The gap of PMLSM is larger and the salient pole effect can be neglected, so direct axis magnetizing inductance is equal to quadrature axis magnetizing inductance, scilicet \( L_d = L_q = L_m \). Because the gap is larger, synchronous inductance \( L_s = L_{so} + L_m \) is also smaller, the armature reaction can be neglected, so the armature winding flux \( \psi_f \) is equal to the flux space vector, the equation is shown as:

\[ F_m = \frac{3\pi}{2\tau} p\psi_f i_q = K_f i_q \]  

Where \( K_f = \frac{3\pi\psi_f}{2\tau} \) is the electromagnetic thrust coefficient.

The equation of mechanical motion is:

\[ \frac{dv}{dt} = \frac{1}{M} (F_m - F_d - F_l - B \cdot v) \]  

Where \( M \) is the total mass of the rotor and the load carried by rotor; \( B \) is viscous friction coefficient; \( F_l \) is load resistance; \( s \) is the rotor linear displacement.

PMLSM model under the d-q synchronous rotating coordinate system can be obtained by the formula (1)-(11), the model is shown in figure 2. Dynamic mathematical model of PMLSM contains coupling terms, scilicet the variables between d-axis and q-axis and the coupling between electrical variables and mechanical variables. Thus, the dynamic process of PMLSM has a nonlinear coupling characteristic.

\[ \frac{1}{L_d} \frac{1}{L_q} \frac{1}{(s+R/L_d)} \frac{1}{(s+R/L_q)} \]  

Figure 2. PMLSM model under the d-q synchronous rotating coordinate system

3. Design of linear servo sliding mode variable structure

In actual control, parameters of control object often vary with its operating environment, so it is difficult to accurately measure or identify these parameters; In addition, external interference is often inevitable, which requires the controller to Parameter changes or external interference has strong robustness. Sliding mode control theory is one of the important methods to study the design of robust control.

Sensorless control strategy of PMLSM, its position angle and speed is obtained by recursive algorithm instead of measuring by position sensors, other parts are consistent with conventional speed control system. The robustness characteristics of sliding mode control theory in the control system have been proposed, taking into account the SMC can effectively suppress torque ripple, so this paper will the SMC apply to the flux observer of PMLSM control system based on vector control, in order to estimate the flux position and speed of the motor.

Sliding mode observer is a mathematical model, the model depends on the structure and parameters of system, can be achieved by DSP programming. The model utilize the difference between estimated value and measured value continually modify the model, in order to eliminate error. The observer mainly includes sliding mode current observer based on the motor model, bang-bang controller, low pass filter
and calculator of flux position angle, finally, after correcting the flux angle, output the rotor position estimated value $\hat{\theta}_r$. The block diagram of the sliding mode observer is shown below in Figure 3.

Figure 3. Position estimation based on sliding mode observer

PMSM mathematical model in the $\alpha$-$\beta$ coordinate system is rewritten as follows, (12) and (13) respectively is the voltage equation and back-EMF equation of PMSM.

$$
\begin{align*}
\begin{cases}
  u_\alpha &= R_\alpha i_\alpha + L_\alpha \frac{di_\alpha}{dt} - \frac{\pi}{\tau} \psi_f \sin \theta \\
  u_\beta &= R_\beta i_\beta + L_\beta \frac{di_\beta}{dt} + \frac{\pi}{\tau} \psi_f \cos \theta
\end{cases}
\end{align*}
$$

(12)

$$
\begin{align*}
\begin{cases}
  e_\alpha &= -\frac{\pi}{\tau} \psi_f \sin \theta \\
  e_\beta &= \frac{\pi}{\tau} \psi_f \cos \theta
\end{cases}
\end{align*}
$$

(13)

3.1. Sliding mode current observer

Sliding model current observer includes the model of current observer and the bang-bang control generator is driven by the error between the estimated value and the measured value. The stator voltage $u_\alpha$, $u_\beta$ as input variables, The back-emf $e_\alpha$, $e_\beta$ and the stator current $i_\alpha$, $i_\beta$ as state variables, $i_\alpha$, $i_\beta$ as the output state, the state equation of system is:

$$
\begin{align*}
\begin{cases}
  i_\alpha &= -\frac{R}{L} i_\alpha - \frac{1}{L} e_\alpha + \frac{1}{L} u_\alpha \\
  i_\beta &= -\frac{R}{L} i_\beta - \frac{1}{L} e_\beta + \frac{1}{L} u_\beta
\end{cases}
\end{align*}
$$

(14)

Against system state equation designed the sliding mode observer, it can obtain the mathematical formula of the observer and control generator, which the equations is shown below,

$$
\begin{align*}
\begin{cases}
  \dot{i}_\alpha &= -\frac{R}{L} \dot{i}_\alpha + \frac{1}{L} (u_\alpha - z_\alpha) \\
  \dot{i}_\beta &= -\frac{R}{L} \dot{i}_\beta + \frac{1}{L} (u_\beta - z_\beta) \\
  z_\alpha &= k \text{sgn}(i_\alpha - i_\alpha) \\
  z_\beta &= k \text{sgn}(i_\beta - i_\beta)
\end{cases}
\end{align*}
$$

(15)

The goal of Bang-Bang controller $z$ makes the current estimation error to zero. It is achieved by proper selection of $k$ and proper estimation of back-emf. The symbol $^\text{#}$ indicates observables.
3.2. Position estimation of the rotor

Back-emf estimation can be obtained by Bang-Bang Controller \( z \), the following formula of low-pass filter as shown as below,

\[
\begin{align*}
\dot{\hat{e}}_a &= -\omega_c \hat{e}_a + \omega_c z_a \\
\dot{\hat{e}}_\beta &= -\omega_c \hat{e}_\beta + \omega_c z_\beta
\end{align*}
\]

(17)

Where \( \omega_c=2\pi f_c \), \( f_c \) is the cut-off frequency of the filter.

Finally, used the sliding mode observer to obtain the estimation value of back-emf, in order to estimate the magnetic pole position. The relationship between back-emf and pole position is:

\[
\hat{\epsilon}_e \sin \theta = \hat{\epsilon}_a = \hat{\epsilon}_\beta = \tau v \psi_f \sin \hat{\theta} \\
\hat{\epsilon}_e \cos \theta = \tau v \psi_f \sin \hat{\theta}
\]

(18)

The estimation value \( \hat{\epsilon}_a \) and \( \hat{\epsilon}_\beta \) of the two-phase orthogonal, back-emf \( e_a \) and \( e_\beta \) can be obtained by the sliding model observer, and can get the pole position \( \hat{\theta} \) of the motor:

\[
\tan \hat{\theta} = -\frac{\hat{\epsilon}_a}{\hat{\epsilon}_\beta}
\]

(19)

As seen the equation (19), when \( \hat{\epsilon}_\beta \to 0 \), \( \tan \hat{\theta} \to \infty \), so the pole position \( \hat{\theta} \) can not be obtained by a simple table lookup. Using the relationship that the moving distance of linear motor rotor is corresponding to an electrical angle of \( 2\pi \) periodic as well as \( \arctan(\tan \hat{\theta}) + \arctan(1/ \tan \hat{\theta}) = 90^\circ \), one period of \( 2\pi \) pole position is divided into eight sections. In each section, according to the size of absolute value of \( \hat{\epsilon}_a \) and \( \hat{\epsilon}_\beta \) decide to take \( \tan \hat{\theta} = |\hat{\epsilon}_a/ \hat{\epsilon}_\beta| \) or \( \tan \hat{\theta} = |\hat{\epsilon}_\beta / \hat{\epsilon}_a| \). Basically, the larger of the absolute value of \( \hat{\epsilon}_a \) and \( \hat{\epsilon}_\beta \) as the denominator. The range of \( \tan \hat{\theta} \) is \([0, 1]\), and the range of \( \hat{\theta} \) is \([0, 2\pi]\).

4. Modelling and simulation analysis

In this paper, the permanent magnet linear synchronous motor vector control system based on sliding mode observer mainly include permanent magnet linear synchronous motor, the estimator of rotor position and speed, speed-loop controller, current-loop controller, the module of Park inverse transform and Clarke transform, generator and inverter of voltage space vector PWM. Based on the principle of analysis of permanent magnet linear synchronous motor, using Matlab/Simulink to build each module of the linear motor control system, so the system model can easily be constructed. The simulation model of control system is shown in figure 4.
The simulation model of pole position estimation based on sliding mode observer is shown in Figure 5. In this figure, will the voltage vector and current vector $u_\alpha$, $u_\beta$, $i_\alpha$, $i_\beta$ in $\alpha$-$\beta$ coordinate system as the input of sliding mode observer, estimates of flux position $\theta^*_e$ and estimates of back-emf $e_{\alpha}$ and $e_{\beta}$ in $\alpha$-$\beta$ coordinate system can be obtained by sliding mode observer. Finally, can build the simulation model of sensorless drive control system of PMLSM based on sliding mode observer.

Before simulation, we need to set some simulation parameters of PMLSM: dc-bus voltage $u_{dc}=96$V, system switching frequency $f_s=20$kHz, effective flux of the permanent magnet $\psi_f=0.11$Wb, number of pole pairs $P=12$, polar pitch $r=15$mm, mass of the rotor $M_r=3.5$kg, stator Inductance $L_d=L_q=L=0.00137$H, stator resistance $R_s=1.778\Omega$, simulation parameters $\omega_0=500$rad/s, $\omega_1=100$rad/s, speed given $v=1.5$m/s.

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**Image Descriptions**

**Figure 4. Simulation model of sliding mode observer**

**Figure 5. Simulation model of PMLSM based on sliding mode observer**
In addition, according to the vector control principle of permanent magnet linear synchronous motor, the given current of d-axis $i_d=0$.

4.1. Analysis of no-load position detection

When the motor no-load that load thrust $F_m$ is 0, the rotor speed of the permanent magnet linear synchronous motor began to accelerate from zero to a steady speed.

The Figure 6 is the waveform comparison between actual position and estimate position for permanent magnet linear synchronous motor based on sliding mode observer. When the system no load, the position angle and its error curve is shown in figure 7. As can be seen from the figure, the position angle deviation of actual flux and estimated flux is not large, the estimated position angle basically can track the actual position angle, and be able to meet the requirements of the vector control. Figure 8 is the back-emf waveform of motor winding is calculated by the control algorithm.

4.2. Analysis of constant load position detection

When the motor starts running, the applied load thrust is 1000N, and in the process to keep the motor load is always the same, namely, the thrust load $F_m$ is 1000N. As shown in figure 9-10, respectively is waveform comparison between actual position and estimate position and three-phase current waveforms, current waveform of $i_d$ and $i_q$. 

\[\text{Figure 6. Comparison of the waveform of actual position and estimate position} \]
\[\text{Figure 7. The waveform of position error} \]
\[\text{Figure 8. The waveform of Back-emf} \]
As can be seen from figure 10, the deviation of actual speed and estimated speed under constant load is not great, the output speed of the measuring module is relatively smooth and good steady-state tracking performance. When the motor is running at low speed, the effect is slightly worse, but estimated speed basically can track actual speed, and be able to meet the requirements of the vector control.

5. Conclusion
The simulation results show that, method for sensorless estimation based on sliding mode observer of PMSLM has some characteristics, such as the system is less affected by motor parameters, can accurately estimate the position and speed of the motor, and can quickly follow the change of the actual position and speed of motor. As can be seen from the simulation curve, we can discover the location and speed curve almost no overshoot, and relatively short time reach steady speed. The speed control system has good anti-disturbance capacity and robustness for parameter change, in addition, it has a good dynamic and static performance. This method has the advantage of high-accuracy speed estimation, strongly robustness of anti parameter change and anti-noise interference. Compared with the traditional vector control method, this method does not require a photoelectric sensor, thereby reducing the system cost and making the volume compact. In this method, the algorithm has a small amount of computation, less demand on hardware, easy to implement.

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