The Research of Sensorless Vector Control for Permanent Magnet Linear Synchronous Motor

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***Abstract*—Permanent Magnet Linear Synchronous Motor has been used widely in the industrial application and transportation system. However, a need of mechanical sensors is a drawback for its control system, which restricts the application range seriously. In order to solve the above drawback, the sensorless vector control method was proposed in the paper. The mathematic model was established for the sensorless vector control of PMLSM, so that it can provide the estimate parameters to realize the sensorless control. According to the extended kalman filter algorithm, the simulation experiment model was constructed to rectify the control performance by estimating the mover speed and position angular instead of the mechanical sensors. The mover speed, position angular and electrical magnet torque were obtained. It is showed that the estimating speed value and position angular value are almost similar as the actual value by using sensorless control method, although it has same disadvantages, such as complex algorithm and a large number of mathematical operations especially the matrix operation. Overall, we can know that the sensorless control method by using extended kalman filter algorithm can substitute the mechanical sensor mode, although it has some disadvatages.**

***Index Terms*—sensorless, vector control, EKF, PMLSM.**

I. INTRODUCTION

The permanent magnet linear synchronous motor is a kind of novel motor. It has some advantages such as high power density, direct drive, fast response, small size and light weight, so it has been widely used in driving the load directly in the industry application [1-3]. For the high performance permanent linear closed-loop driving system, it realized the precision speed and position control by fixed speed and position sensors to test the mover speed and position, the sensors usually are photoelectric encoder, hall sensor, eddy current sensor, rotary encoder, grating ruler and so on. However, the using of mechanic sensor not only increases the cost of drive equipment, but also makes the driving system much larger and unstable [4]. In recent years, the sensorless control systems have been researched to solve the above disadvantages. It can eliminate the need for speed and position sensors, so the structure of control system is more simple, the costs is reduced, meanwhile, the stability and control precision are improved[5]. With the rapid development of control theory, digital signal processing and computer technology, the sensorless vector control technology is researched more widely.

The position and velocity sensorless control of PMLSM drive can overcome above difficulties. Some sensorless control methods have been proposed. There are stator observer estimation method, flux linkage estimation method, high frequency injection method (HF) , inductive method, Back EMF, model reference adaptive method and based on artificial intelligence, etc, as following [6].

Based state observer estimate method is the state reconstruction, it takes the speed, flux linkage, rotor angular and current as stator variable, then constructs a new system based on the status variable, taking the direct measurement variables in the original system as input signals to reconstruct the output variables equal to the original system status under certain conditions. The usual observe are reduced order state observer, full order state observer, extended kalman filter and sliding mode observer. (a) Reduced order state observer. For the nonlinear system, the observe is added a correction term on the base of original state equation, its gain matrix is the function of state estimator, input and output different from the linear observe.(b) Full order state observer. It is an optimum linear estimate algorithm, it considers the system model error and the statistical properties of measurement noise, but it must use high-speed and high-precision digital signal processor to complete complex algorithm.(c) Extended Kalman Filter(EKF).Taking the stator current and rotor flux linkage as state variable，

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taking the speed as state equation parameter to realize linearization and estimate the speed. Although the algorithm is more complex, it can obtain good features.(d) Sliding mode observer. According to the strong robustness characteristics, the sliding mode observer makes the usual state observer control loop revise as sliding mode variable structure, then using high frequency structure transformation switch to change. Because of the essence of discontinuous switching control for sliding control, the system will shake and cause torque ripple, it is adverse to the low speed vector control.

Based flux linkage estimate method can estimate the flux linkage by measuring the stator voltage and current, then we can calculate the rotor position and speed according to the relationship between flux and rotor position. The flux linkage estimation has three kinds of methods: based two phase static coordinate, based static three phase coordinate rotor position estimated and stator flux linkage estimated.

Induce method is used in salient pole permanent magnet synchronous motor, the winding inductance is seen as a function of rotor position to calculate the rotor position. The method has a better high-speed and low-speed tracking performance. The load current increases, the error will be increased significantly, so that we must take some compensatory measures.

Based back-EMF is a kind of rotor position signal control method by measuring the armature EMF. It contains EMF zero crossing detection, third harmonic detection, EMF integration method and fly-wheel diode.

Model reference adaptive method takes the without unknown parameters equation as reference model and the estimated parameters equation as adjustable model. The parameters of adjustable model are adjusted real-time using appropriate adaptive law constituted by the error of two model output, so that the output of control object can track the output of reference model. Exceptly Some other intelligent control algorithm.

II. THE TWO MAIN TYPES OF SENSORLESS CONTROL

Among above one group is methods based on motor fundamental equations. Rotor flux is considered as sinusoidal distributed, which neglects motor space harmonics and other secondary effects. Then motor back-EMF can be used to estimate rotor position from motor fundamental equations. These methods are either open loop structure or closed loop observers. Open loop methods have a straightforward structure which is easy for calculating. But the estimation is greatly influenced by motor parameters variation and current measurement noise. In order to increase the robustness and to improve the dynamics of the estimation, it is necessary to use the error signals between the measured and estimated quantities as a feedback, thus composing a closed loop observer.

When motor is at low speed, motor back-EMF is relatively small, and can not be used to precisely identify motor position information. According to the adverse,the transient excitations can be used by injected signals having other frequencies than the fundamental (HF injection), or transients caused by inverter switching, to reliably identify and track rotor position even when the rotor is at standstill.

HF injection sensorless control shows good rotor position estimation result at low range. It is insensitive to parameter inaccuracy. Another advantage is that, for a PM motor whose saliency is not very prominent, flux saturation effect can be utilized by using d-axis signal injection method. Yet in this method many filters are used for signal processing, which will inevitably introduce phase delay and magnitude decrease. In this paper a simplified HF injection method is proposed aiming at reduce number filters that are used.

HF injection sensorless control is based on motor magnetic saliency phenomenon. In this method a high frequency voltage or current vector signal is superimposed on motor fundamental excitation. The corresponding high frequency current (or voltage) signal contains rotor position information, and is analyzed to track spatial saliencies and to estimate the rotor or flux position[7].

Another group is simple and greatly depended on accuracy of the parameter. There are methods based on back electromotive force(EMF), state observers and extended Kalman filters EKF)，model reference adaptive system(MRAS) . Methods based on EMF and MRAS. Method based on state observer is more robust because of feedback correction. but it is difficult to determine all the feedback gains in order to get both better stability and quicker converging speed. EKF is an optimal estimator in the least-square sense for estimating the states of dynamic nonlinear system and it is, thus, a viable and computationally efficient candidate for the online determination of position and speed . The difference between state observer and EKF is that the feedback gain of EKF is updated automatically by iteration based on optimal control theory[8].

Sensorless closed-loop control system can estimate the speed and position by mathematic algorithm according to the stator voltage and current, so that the traditional mechanic sensor method is substituted. Nowadays, there are some usual sensorless estimated method[9-12], such as model reference adaptive method[13], full-order state observer method[14], kalman filter method , sliding mode observer method and so on[15-18]. According to the stator voltage and current, the electromagnetic estimation method can estimate the rotor speed and position by motor mathematic equations. The special performance analysis method can obtained the rotor position by testing the rotor space salient, magnetic circuit structure and magnetic saturation characteristics, such as current harmonic analysis and high frequency injection method. The observer identification method makes the output varies as the state observer, compares the observer output with the real testing value, then correct the observer estimated value by the error. The usual methods are full-order state observer method, adaptive observer, variable structure observer and kalman filter observer and so on[19-10].In the paper, the observer identification method was used to estimate the mover speed and position, so that the sensorless control was realized for permanent magnet linear synchronous motor.

III. The Sensorless Control System of Permanent Magnet Linear Synchronous Motor

A. *The Mathematic Model of Permanent Magnet Linear Synchronous Motor*

Assuming that the hysteresis loss, eddy current loss and magnetic saturation effects of PMLSM are negligible, the permanent magnet can produce sine wave magnetic field. So the mathematic mode of PMLSM in the *d*-*q* coordinate system can be described as follows [11]:

The stator voltage equations are given by:

$$u_d = R_s i_d + p\psi_d - \omega_r \psi_q \,. \tag{1}$$

$$u_q = R_s i_q + p\psi_q + \omega_r \psi_d \,. \tag{2}$$

The equations of stator flux linkage are:

$$\psi_d = L_d i_d + \psi_f \,. \tag{3}$$

$$\psi_q = L_q i_q \,. \tag{4}$$

Taking the flux linkage equations into voltage equations, the new equations as follows:

$$u_d = (R_s + pL_d) i_d - \omega_r L_q i_q \,. \tag{5}$$

$$u_q = (R_s + pL_q) i_q + \omega_r L_d i_d + \omega_r \psi_f \,. \tag{6}$$

Combine the (5) and (6), their matrix equation as (7):

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega_r L_q \\ \omega_r L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r \psi_f \end{bmatrix} . \tag{7}$$

Taking the voltage *u* as known input variable, current *i* as output variable in (7), the system model equation $\dot{x} = Ax + Bu$ are:

$$\frac{di_d}{dt} = \frac{1}{L_d} u_d - \frac{R_s}{L_d} i_d + \omega_r \frac{L_q}{L_d} i_q \,. \tag{8}$$

$$\frac{di_q}{dt} = \frac{1}{L_q} u_q - \omega_r \frac{L_d}{L_q} i_d - \frac{R_s}{L_q} i_q - \frac{\omega_r \psi_f}{L_q} \,. \tag{9}$$

In the above equations, *p* is differential operator, R_s is armature winding resistance, ω_r is mover angular velocity, ψ_f is a constant the permanent magnets flux linkage, L_d is the self-inductance of *d* axis coil, L_q is the self-inductance of *q* axis coil.

Electromagnetic torque equation is:

$$\begin{aligned} T_e &= \frac{3}{2} p_n (\psi_d i_q - \psi_q i_d) \\ &= \frac{3}{2} p_n [\psi_f i_q + (L_d - L_q) i_d i_q] \end{aligned} \,. \tag{10}$$

Mechanical motion equation of mover is:

$$J \frac{d\omega_r}{dt} = p_n (T_e - T_L - B \frac{\omega_r}{p_n}) \,. \tag{11}$$

The speed of mover is:

$$\omega_r = \frac{d\theta}{dt} \,. \tag{12}$$

The velocity equation is:

$$v = r\omega_r \,. \tag{13}$$

Where p_n is the number of pole pairs, T_e is electrical torque, T_L is load torque, *J* is moment of inertia, *B* is damping, θ is the position of mover, *v* is mover speed.

According to the PMLSM mathematic model, the stator equation parameter of the speed and position estimating can be provided for sensorless control system.

B. *The Control Structure of PMLSM*

According to the sensorless control principle, the real time speed and mover position can be estimated through the stator terminal voltage and phase current, so that we can construct the sensorless control for PMLSM structure as Fig.1.

The control scheme mainly contain several control modules, they are stator current detection, sensorless calculator for rotor position and speed, speed loop regulator, Clark conversion, Park transformation and inverse transformation, and voltage PWM control modules. It is realized as the following procedures, the rotor space position, speed and electrical angle are calculated by sensorless control, the *q* axis reference i_q^* of stator current is output from the PI speed regulator. The stator phase current is detected through current sensor, then it is decomposed to obtain the *dq* axis component i_d and i_q, the space vector voltage *dq* axis component u_d and u_q are forecasted through the current regulator, the PWM signal drive the inverter to provide the voltage to PMLSM, so that we can obtain the high efficient control method for PMLSM.

IV. The EKF Forecast Algorithm of Mover Speed and Position

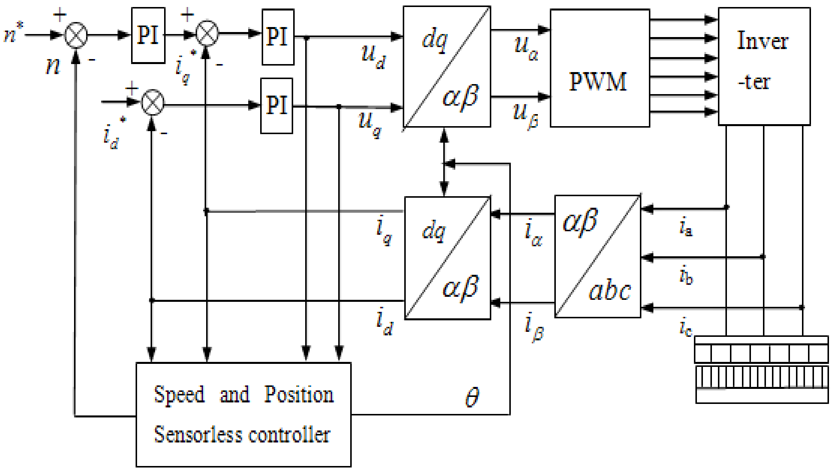

Figure 1. The Principle of sensorless vector control

A. The Extend Kalman Filter Equation of PMLSM

The mover speed and position can be obtained by observer in the sensorless control system, the EKF was adopted to make iterative approximation, so that we can obtain the nonlinear discrete estimation value[22].

Taking the system state variable as $x = \left[i_d, i_q, \omega_r, \theta\right]$,

Input variable is: $u = [u_d, u_q]^T$, output variable is: $y = [i_d, i_q]^T$.

In order to estimating the mover speed and position by using EKF in the *d-q* rotator coordinate system, the mover speed ω_r and position angular θ must be increased as new state variable. Assuming that the sampling period is small and load inertia is large, so that the speed changing can be omitted, that is $\frac{d\omega_r}{dt}$. When the speed is taken as a constant, the motor mathematic mode can be a linear system for the PMLSM. Then the linear system (14) and (15) can be obtained according to the (8) and (9) for the PMLSM.

$$\begin{bmatrix}\dot{i}_d\\ \dot{i}_q\\ \dot{\omega}_r\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r\frac{L_q}{L_d} & 0 & 0\\ -\omega_r\frac{L_d}{L_q} & -\frac{R_s}{L_q} & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix} i_d\\ i_q\\ \omega_r\\ \theta\end{bmatrix} + \begin{bmatrix}\frac{1}{L_d} & 0\\ 0 & \frac{1}{L_q}\\ 0 & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}u_d\\ u_q\end{bmatrix}. \quad (14)$$

$$+\begin{bmatrix}0\\ -\omega_r\frac{\psi_f}{L_q}\end{bmatrix}$$

$$\begin{bmatrix} i_d\\ i_q\end{bmatrix} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix} i_d\\ i_q\\ \omega_r\\ \theta\end{bmatrix}. \quad (15)$$

That means the system state equation is $\dot{x} = Ax + Bu + w(t)$.

The measure state equation is $y = Cx + v(t)$.

Where

$$A = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r\frac{L_q}{L_d} & 0 & 0\\ -\omega_r\frac{L_d}{L_q} & -\frac{R_s}{L_q} & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}, B = \begin{bmatrix}\frac{1}{L_d} & 0\\ 0 & \frac{1}{L_q}\\ 0 & 0\\ 0 & 0\end{bmatrix},$$

$$C = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}.$$

$w(t)$ and $v(t)$ is the system noise matrix and measurement noise matrix respectively, the former noise is produced by the imprecise mode and system disturbances, the latter noise is produced by the inaccuracy measurements, the both are assumed to be zero mean Gaussian noise, their variance matrix is Q and R respectively.

Assuming the sampling period is T, the system state equation and measurement state equations are discretization, so the discretization state parameter are:

$$A(k) = I + AxT = \begin{bmatrix} I - \frac{R_s}{L_d}T & \omega_r\frac{L_q}{L_d}T & 0 & 0\\ -\omega_r\frac{L_d}{L_q}T & I - \frac{R_s}{L_q}T & 0 & 0\\ 0 & 0 & I & 0\\ 0 & 0 & T & I\end{bmatrix},$$

$$B(k)=\begin{bmatrix} \frac{1}{L_d}T & 0 \\ 0 & \frac{1}{L_q}T \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad , \quad C(k)=\begin{bmatrix} T & 0 & 0 & 0 \\ 0 & T & 0 & 0 \end{bmatrix}$$

The discretization state equation are (16) and (17)

$$\Delta x(k+1)=A(k)\Delta x(k)+B(k)u(k)+w(k)\,. \qquad (16)$$

$$\Delta y(k)=C(k)\Delta x(k)+v(k)\ . \qquad (17)$$

B. The Kalman Filter Forecast Estimate Algorithm

According to the EKF algorithm step, the EKF recursive algorithm is divided into filter calculation circuit and gain calculation circuit, meanwhile the former is divided into time update and measurement update stage.[23]

The first step forecast is：

$$\Delta x(k,k-1)=A(k,k-1)\Delta x(k-1)\,. \qquad (18)$$

Forecast error variance is:

$$\begin{aligned} P(k,k-1)=A(k,k-1)P(k-1)A^T(k,k-1) \\ +Q(k-1) \end{aligned}\,. \qquad (19)$$

Gain formulation is：

$$K(k)=P(k,k-1)C^T(k)\begin{bmatrix} C(k)P(k,k-1) \\ C^T(k)+R(k) \end{bmatrix}^{-1}. \qquad (20)$$

Filtering formulation is：

$$\Delta x(k,k)=\Delta x(k,k-1)+K(k)\begin{bmatrix} y(k)-C(k) \\ \Delta x(k,k-1) \end{bmatrix}. \qquad (21)$$

Filtering variance is

$$\begin{aligned} P(k)=\left[I-K(k)C(k)\right]P(k,k-1) \\ \left[I-K(k)C(k)\right]^T+K(k)R(k)K(k)^T \end{aligned}\,. \qquad (22)$$

From the (18) to (22) five steps iteration procedure as Fig.2, the mover speed and position can be estimated for PMLSM by using EKF. In the process, the initial value of state error covariance matrix $p(k,k)$ is setting as $p(0)$, system noise variance Q and measurement noise R are determined based on overall system performance.

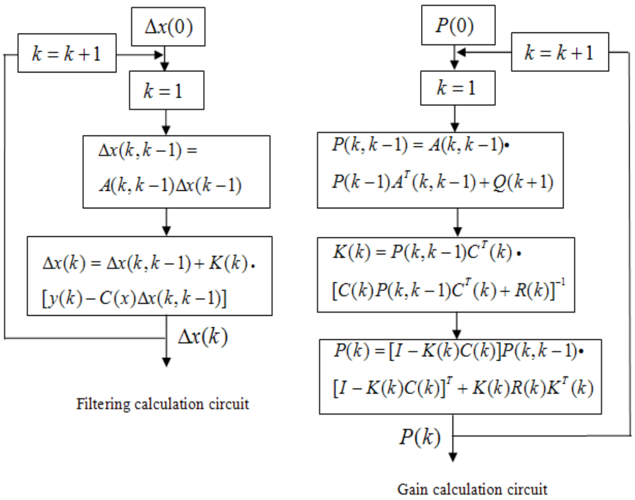

Figure 2. Filtering calculation iterative process

V. SYSTEM SIMULATION EXPERIMENT

A. System Simulation Model

According to the mathematic model of PMLSM and the Extend Kalman Filter control principle, the sensorless control simulation mode of PMLSM was constructed as Fig.3.

The simulation model mainly contains of two parts, the vector transformation and EKF algorithm estimator. The former part is Park transformation and Clark transformation. It realizes the transformation from a-b-c three phase static coordinate to d-q two phase dynamic coordinate, and the transformation from d-q two phase dynamic coordinate to a-b-c three phase static coordinate. The latter is EKF algorithm estimator, which obtains the feedback speed and compares with the given speed. The two parts take speed and current double closed-loop constitute the speed and current feedback system. Then it adopts the $i_d = 0$ method using PWM mode to drive the universal bridge controlling the motor. The control model can estimate the mover speed and position angular, so that the sensorless control of PMLSM was realized.

B. System Simulation Results

The sensorless control of PMLSM based on EKM can be verified through the experiment simulation. The system simulation parameters are given as follows:

Number of pole pairs is 3, flux of permanent magnet ψ_f is 0.2324*Wb*, rotor resistance R_s is 1 Ω, *d* axis inductance L_d is 13.91*mh*, *q* axis inductance L_q is 13.91*mh*, viscous friction coefficient *B* is 0.1N • s/m, rotor mass is 96*kg*, pole pitch τ is 39*mm*.

In the experiment, the given load torque was 1000N • M and velocity was 3.0m/s, at 0.2s the load torque was changed as 1000N • M. In EKF controller, the

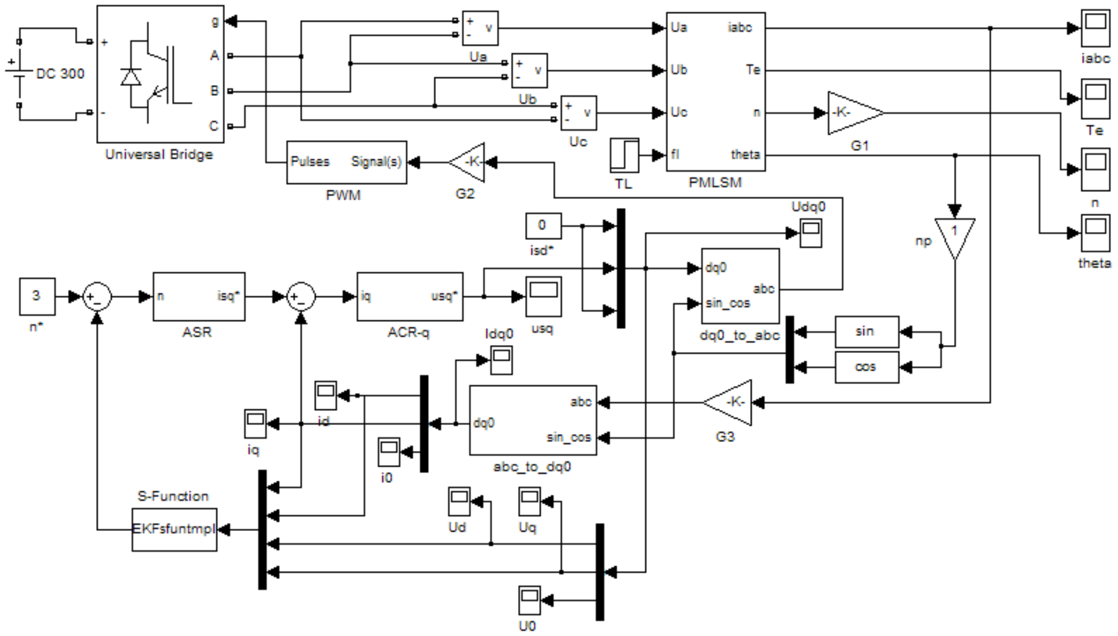

Figure 3. Sensorless simulation mode

initial state vector is: $x(0)=[0 \quad 0 \quad 0 \quad 0]^T$, its covariance matrix and initial value as follows:

$$P(0)=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&10&0\\0&0&0&1\end{bmatrix},\ Q=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&10&0\\0&0&0&0.1\end{bmatrix},$$

$$R=\begin{bmatrix}0.1&0\\0&0.1\end{bmatrix}.$$

In the whole simulation process, the system simulation time is 0.5s, the mover speed was obtained as Fig.4. It shows that there is only a little fluctuate at the starting instant, the little fluctuate almost can be omitted. At the 0.2s, the load was loaded, we can see that although it has a little fluctuate.It is less than the starting instant's fluctuate. From Fig.4, we can known that the EKF estimating sensorless method can obtain well control effects, the EKF estimate speed is almost similar as the actual value, the sensorless control system has smooth start effect and loading ability.

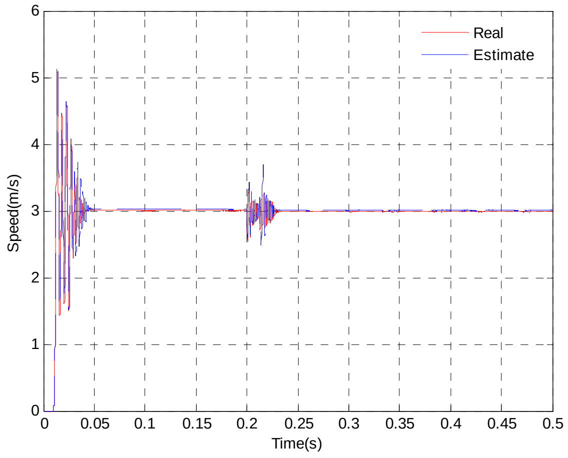

Figure 4. Speed comparison chart

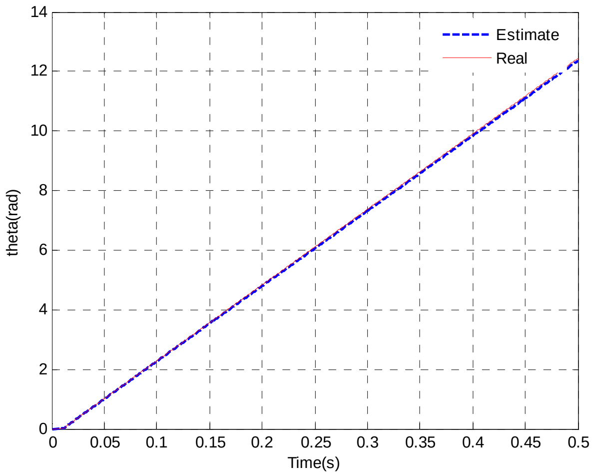

Figure 5. Position angular comparison

The mover position angular simulation result as Fig.5, in the whole simulation stage, the EKF estimate position angular is similar as the actual position angular completely, it shows that the estimate value can fully track the actual value.

The electrical magnetic torque as Fig.6, there is only little torque fluctuate at 0.01s, other torque fluctuates can be omitted at the starting instant. At 0.2s, the load was

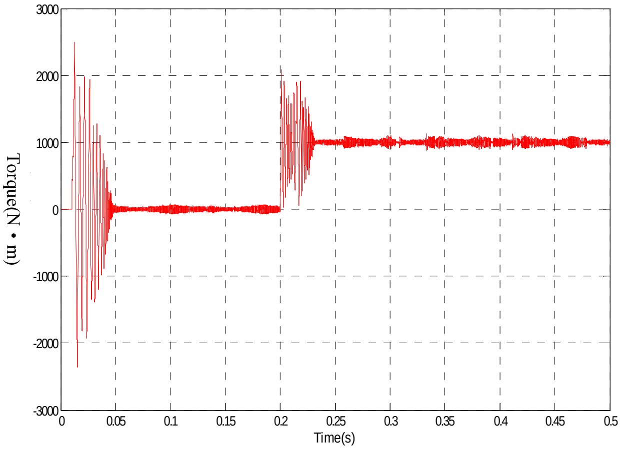

Figure 6. Electrical magnetic torque.

loaded, although it has a little torque fluctuate, the electrical magnetic torque of PMLSM can track the load torque real-timely. We can know that the control system has well load torque tracking ability, the electrical torque can meet the load demand completely.

VI. RESULTS AND DISCUSSION

From the system construction and simulation analysis, it is showed that EKF algorithm can realized the sensorless control of PMLSM, the sensorless estimate method can track the mover actual speed and position angular perfectly, so that the speed and current double closed-loop sensorless control is realized by using the EKF sensorless control algorithm to substitute the mechanical sensor. Meanwhile, it still has some disadvantages, such as complex algorithm, a large number of mathematical operations especially the matrix operation. The sensorless control needs much higher hardware configuration and computing speed.

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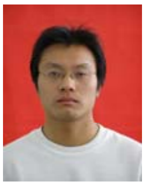

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