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Control System Research of Adaptive Observer for PMLSM

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ABSTRACT

Adaptive observer method is a widely used method, which includes a reference model and adjustable contained identification parameters. Its speed adaptive law is derived by Popov ultra-stability theory, which ensures the asymptotic convergence of the parameter estimates, and it has a good dynamic performance. The control system using space vector control method, and the implementation process of vector control on permanent magnet linear synchronous motor is analyzed particularly, we also give the modules of control system in Matlab/Simulink. Through the results, we can verify the reliability of the speed sensorless control method. The problem of instability in the low-speed electric mode according to the observer linearization method was analyzed. To solve the problem, the observer augmented with a signal injection technique was researched. The simulation results show that the method is effective to enhance the system parameter robustness and speed observation, improve low-speed performance of the speed-sensorless vector control system.

Key words: permanent magnet linear synchronous motors (PMLSM); Adaptive Speed Estimator; Speed-sensorless vector control; Popov Stability Theorem

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INTRODUCTION

Permanent magnet linear synchronous motor mover uses a permanent magnet structure, simplifying the physical structure of the mover, with a better performance in terms of efficiency and positioning accuracy [1].

Usually a method of controlling the system by controlling the speed or position of the motor to control the servo system, thus speed closed-loop control is the necessary part; the speed can be obtained through a raster or a magnetic sensor grid generally [2-3]. With the rapid development of power devices and control chip of a stronger computing functions, motor control methods tend to become more perfect and precise, and at the same time, due to the applications of linear motor in the filed of rail transportation, the speed sensorless control method has become a hot destination and put forward many practical methods[4]. Efficient computational methods can be divided into two categories: (1) the fundamental incentive approach relies on a mathematical model of the motor, such as adaptive closed-loop observer method or back-emf method, both have a good dynamic performance under the condition of high speed, however, due to the strong dependence on motor parameters, the rotor position and speed identification will be easy to fail within the scope of the zero speed and low speed[5-6]; (2) high-frequency signal injection method, the use of motor saturation effects, injects high frequency voltage (current) signal to the motor system by extracting the exact location information of the rotor from the response signal, the rotor position can be tracked at low speed, has good robustness[7-8].

In this paper, a stable adaptive observer is studied, and permanent magnet linear synchronous motor speed estimation method is obtained by using Popov stability theory. In the condition of low speed, the high-frequency signals can generate the rotor position error response, thus injecting a high-frequency voltage signal to the motor control system, to adjust the output of the adaptive observer and improve the dynamic performance of the system.

CONTROL SYSTEM MODEL OF ADAPTIVE OBSERVER

In this section, the PMLSM model and control problem are formulated, and the used PMLSM is depicted in Fig 1.

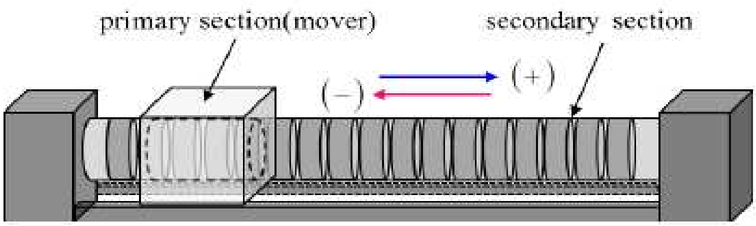


Figure 1 Permanent Magnet Linear Synchronous Motor.

In the adaptive observer, using the amount of error between the reference model and adaptive model, we can get the rotor speed and position information via an adaptive regulator.

Under the *dq* coordinate system in sync with the rotation of rotor magnetic field, PMLSM stator voltage equation is[9]:

$$u_s = R_s i_s + \dot{\psi}_s + \omega_m J \psi_s \qquad (1)$$

Where: u_s and i_s is respectively expressed stator voltage and current, $u_s = [u_d u_q]^T$, $i_s = [i_d i_q]^T$; ψ_s showing stator flux linkage, $\psi_s = [\psi_d \psi_q]^T$; R_s said stator resistance; ω_m said rotor electrical angle frequency, $\omega_m = \dot{\theta}_m$; $J=\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

The equation of stator flux linkage ψ_s is expressed as:

$$\psi_s = L i_s + \psi_{pm} \qquad (2)$$

Where: ψ_{pm} is expressed as the excitation flux linkage of permanent magnet, $\psi_{pm} = [\psi_{pm} \quad 0]^T$. $L=\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}$, L_d and L_q is respectively expressed as the equivalent inductance of *d* and *q* shafting.

According to the equation (1) with equation (2), the mathematical model of adaptive observer can be obtained as following:

$$\dot{\hat{i}}_s = (-R_s L^{-1} - \hat{\omega}_m L^{-1} J L)\hat{i}_s + L^{-1} u_s - \hat{\omega}_m L^{-1} J \psi_{pm} + H \Delta i_s \qquad (3)$$

Where, the superscript"$\wedge$"indicates the observed value; Δi_s is stator current error, $\Delta i_s = i_s - \hat{i}_s$; *H* is the error feedback matrix of adaptive observer, in order to be able to configure any observer poles in the complex plane, *H* is often represented as a symmetric matrix : $H = h_1 I + h_2 J$. is shown in Figure 2.

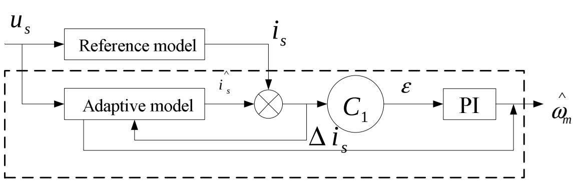


Figure 2 Block diagram of the adaptive observer.

To the motor itself as a reference model, observer includes the estimated speed of the motor. A stator current error by acting adaptive law on speed, can identify the motor speed and instantaneous feedback to the adjustable model; using adaptive observer for speed estimation, error feedback matrix constitutes a progressive state observer.

Finally the error term of adaptive observer is got.

$$\varepsilon = C_1 \Delta i_s \qquad (4)$$

Where : $C_1 = \lfloor 0 \quad L_q \rfloor$。

By using the PI controller to make the observation of faster convergence, the estimated motor speed is:

$$\hat{\omega}_m = -k_p \varepsilon - k_i \int \varepsilon dt \qquad (5)$$

Wherein, k_p, k_i are for the coefficients of adaptive PI controller, the estimated electrical angle $\hat{\theta}_m$ is obtained by the integral $\hat{\omega}_m$.

3.THE SUPER-STABILITY ANALYSIS OF POPOVA STABILITY THEORY

Based on the theory of super-stable design method, speed estimation method of permanent magnet linear synchronous motor is obtained. Popov super stability theorem determines the adaptive observer of permanent magnet synchronous motor with the adaptive law design based on the above stator resistance and rotor flux linkage is stable[10].

So $L_d = L_q = L_s$, by the PMLSM stator voltage equation under the dq-axis can get its current mathematical model:

$$\frac{di_d}{dt} = -\frac{R_s}{L_s} i_d + \frac{\pi}{\tau} V i_q + \frac{u_d}{L_s} \qquad (6)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_s} i_q + \frac{\pi}{\tau} V i_d + \frac{u_d}{L_s} - \frac{\varphi_f}{L_s} \frac{\pi}{\tau} V \qquad (7)$$

Adjustable parallel model formula can be abbreviated as follows:

$$\frac{d}{d_t} \hat{i}^* = A \hat{i}^* + B \hat{u}^* \qquad (8)$$

$\hat{V}$ is expressed as the estimated speed of MRAS, so that the state variable error is *e*, $e = i^* - \hat{i}^*$. The state equation of the parallel adjustable model will rewrite as the following form:

$$\frac{de}{dx} = Ae - Iw \qquad (9)$$

$$V = De \qquad (10)$$

Among them, $w = (\hat{A} - A)\hat{i}^*$, so that D = I, then V = e.

To make the design of MRAS system is asymptotically stable, it needs to meet two conditions of the Popov super stability theory:

1) Linear forward square is strictly positive real, namely transfer matrix $H(s) = D(sI - A)^{-1}$ is strictly positive real matrix.

2) $\eta(0,t) = \int_0^t V^T w dt \geq -\gamma_0^2$, $\forall t \geq 0$, γ_0 is an arbitrary finite positive number. The model reference adaptive system is asymptotically stable.

Depending on the PI regulation, the estimation of the speed formula is expressed as:

$$\hat{v} = \frac{\tau}{\pi}\int_0^t k_1 (i_d \hat{i}_q - i_q \hat{i}_d - \frac{\varphi f}{L_s}(i_q - \hat{i}_q)) + \frac{\tau}{\pi}\int_0^t k_2 (i_d \hat{i}_q - i_q \hat{i}_d - \frac{\varphi f}{L_s}(i_q - \hat{i}_q)) + \hat{v}(0) \tag{11}$$

Electrical and mechanical angles as follows:

$$\hat{\theta} = \int_0^t \frac{\tau}{\pi}\hat{V}dt \tag{12}$$

ENHANCED MRAS MODLE

In low-speed region, the identification error of adaptive observer leads to failure recognition and causes instability in the system. In order to improve the adaptive observer, the high frequency voltage injection method is used to correct it[11-12]. High-frequency AC voltage signal is loaded to the d-axis:

$$u_c = \hat{u}_c \cos(\omega_c t) \tag{13}$$

Where: $\hat{u}_c$ is amplitude; ω_c is frequency.

Magnetic circuit saturation caused the salient pole effect, so under the high frequency excitation, the inductance of *d* and *q* axis is no longer equal, and high frequency current response i_{dc}, i_{qc} contains information of the rotor position error. With the current response components of *q* shaft to estimate the rotor position, i_{qc} is as an input signal to observe the rotor position information accurately. First, fundamental frequency current component and harmonic components of the inverter switching frequency can get i_{qc}, using the sin ($\omega_c t$) signal to demodulate the high-frequency current signal i_{qc}, and finally a low-pass filter (LPF) can get the rotor position error signal:

$$\lambda = LPF\{i_{qc}\sin\omega_c t\} \tag{14}$$

The signal extraction diagram is shown in figure 3.

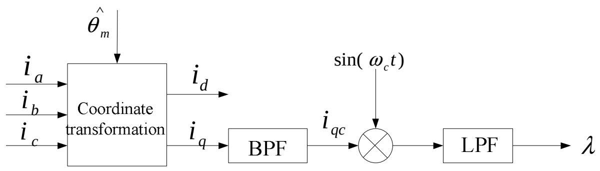


Figure 3 The signal extraction diagram.

The role of PI regulator is to eliminate the error signal, to realize the rotor position tracking without deviation. The rotor position error signal of the PI controller generates a correction signal for correcting an adaptive model.

After correction, the observer model can be represented as:

$$\dot{\hat{i}}_s = (-R_s L^{-1} - \hat{\omega}_m L^{-1} JL)\hat{i}_s + L^{-1}u_s - (\hat{\omega}_m - \omega_\lambda)L^{-1}J\psi_{pm} + H\Delta i_s \tag{15}$$

$$\omega_\lambda = r_p\lambda + r_i\int\lambda dt \tag{16}$$

At low speeds, MRSA and high frequency injection method interact simultaneously: at the moment of motor starts, first of all, the high-frequency signal injection is to accurately track the position of the rotor; after the speed increases to a certain value, the adaptive observer begins to identify the stability. When the speed increases up to a certain value, the adaptive observer will be as a separate role for carrying speed estimation. In order to achieve a smooth transition between two rotation speed region, the amplitude value of the injection parameters and the error signal of the PI regulator parameter value are to be decreased linearly with the speed of rise, the high frequency signal will terminate the injection when the rotational speed rises to ω_t.

SIMULATION ANALYSIS OF THE CONTROL SYSTEM

The main idea of model reference adaptive identification can be summarized as follows: Choose the equation with unknown parameters as adjustable model, and the equation without unknown parameters as reference model. Both models have outputs with the same physical significance. When two models work at same time, parameters of adjustable model can be real time regulated by using the difference value between their outputs based on the adaptive law, so as to achieve the goal of tracing reference model by controlling the output. In this case, choose PMLSM as reference model, and current model as adjustable model. Rotor speed can be estimated by proper adapting adjustment, on the basis of the differences between the output d-q current values of the two models. The rotor angle can be derived through an integration of the speed.

Fig.4 shows the sensorless vector control system of PMLSM. The field oriented control is established under d-q coordinate system. The estimated speed is compared with the given speed, and the difference value is put into a PI controller, then the given torque current i_q can be calculated. Torque voltage can also be got from PI controllers by adjusting the torque current errors. After the coordinate transformation, voltage signals are used for SVPWM to generate PWM control signal, and drive the inverse bridge. Thus, double close loop vector control with feedback of speed and current are realized.

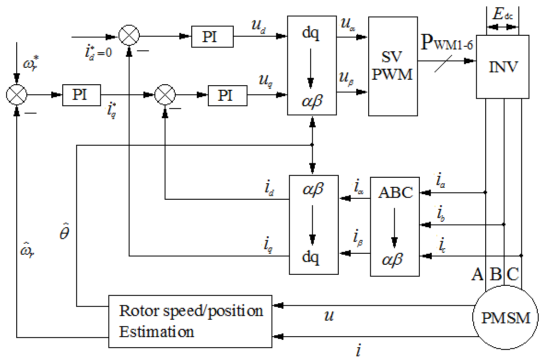


Figure 4 Sensorless vector control system of PMLSM.

The system uses a table-mounted 4-pole permanent magnet synchronous motor, the specific motor parameters as shown in Table 1.

TABLE I. **Simulation Parameters Table of PMLSM**

Project Name	Value
Rated speed	2000 r/min
Rated torque	7.5 N.M
Stator flux	0.38Wb
Stator resistance	0.6Ω
Number of pole pairs	2
Stator Inductance	3.1mH
Moment of inertia	9.6 kg.cm2
DC bus voltage	310V
Switching frequency	12.5 kHz
High-frequency voltage amplitude	31 V
High-frequency voltage frequency	1 kHz
Critical speed	20.94rad/s

The main Simulink module of MRAS method is shown as Fig.5 to Fig.7.

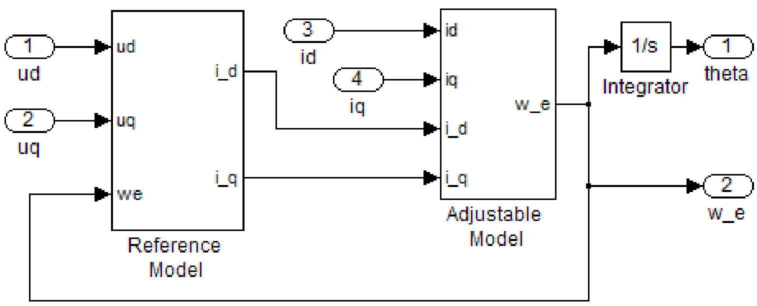


Figure 5 Speed and angle estimation module based on MRAS.

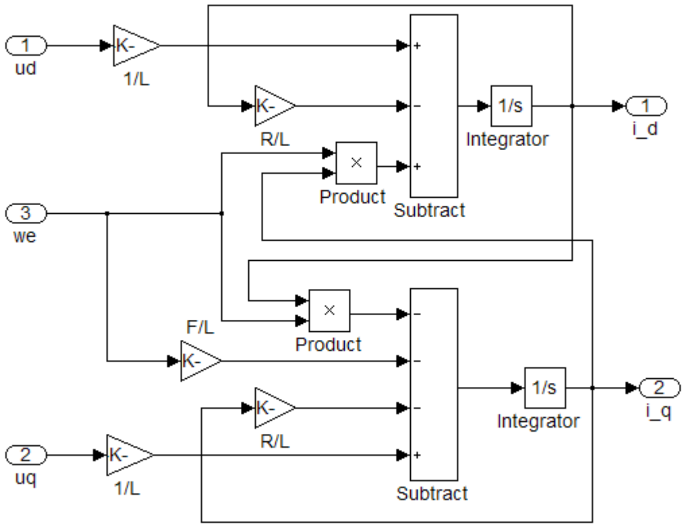


Figure 6 Adjustable Model.

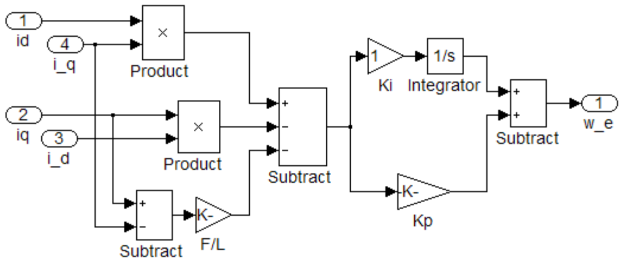
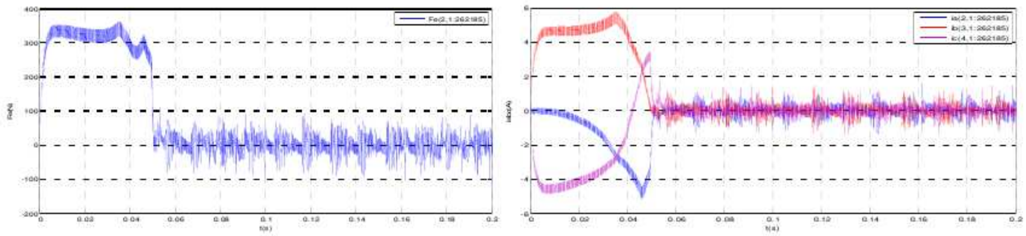
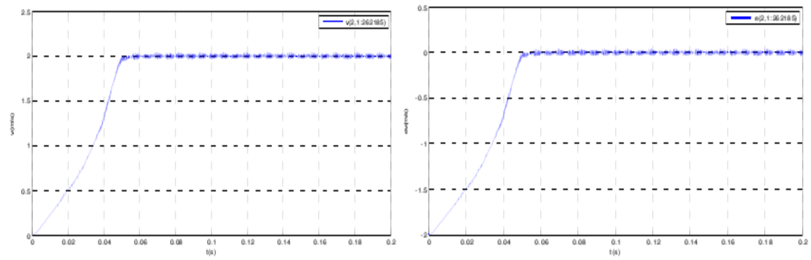


Figure 7 Adaptive law

1) The figure 8 shows that the motor electromagnetic torque decreases with the speed increases until it reaches the rated speed, torque ripple in the vicinity 0N, its start-up current is gradually reduced from large to stabilized. And the use of adaptive observer calculated velocity curve can be a good tracking simulation speed curve of the motor.



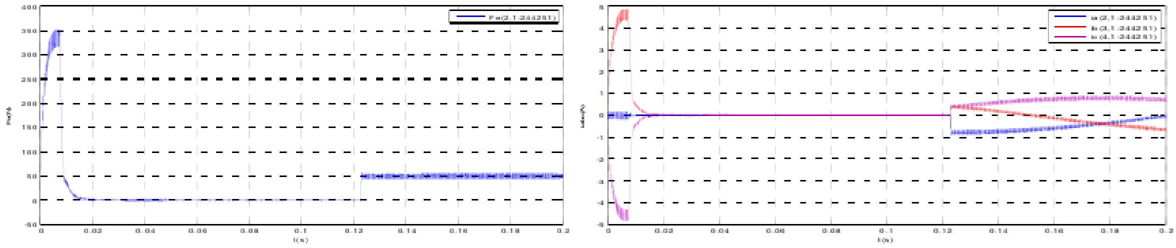
(a) Torque waveform (b) Three-phase current waveforms



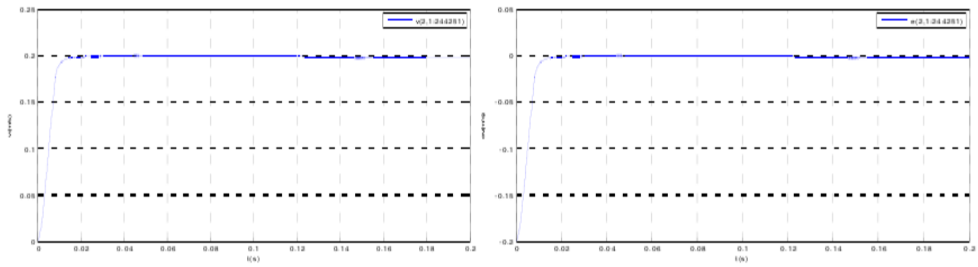
(c) Velocity waveform (d) Velocity waveform error

Figure 8 Waveform of the motor parameters when load is 0N, speed is 2 m/s

2) Given the speed of 0.2 m/s, motor related parameters of waveform are shown in figure 9 (a) ~ 9(d) when the load at the time of 0.1 s is from 0 N to 50 N.The figure shows that before 0.1 s, the motor electromagnetic torque increases with the speed. Gradually reduced to 0 N, after the sudden increase in load, for the sake of system stable operation at the rated speed, the electromagnetic torque increases, the three phase current increases to enhance the ability of the motor load. Its speed stability in rating, little fluctuation, and speed calculated curve by using the adaptive observer is good for tracking the simulation speed curve of the motor.



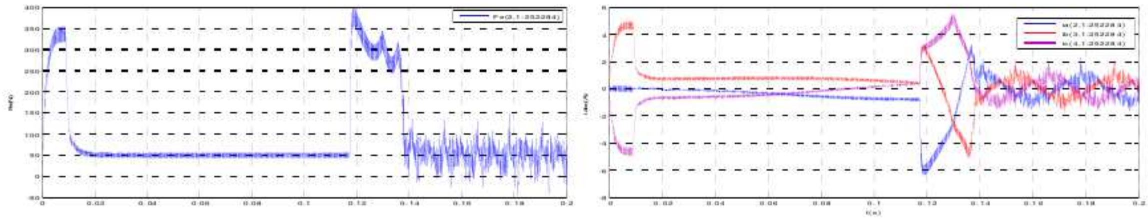
(a) Torque waveform (b) Three-phase current waveforms



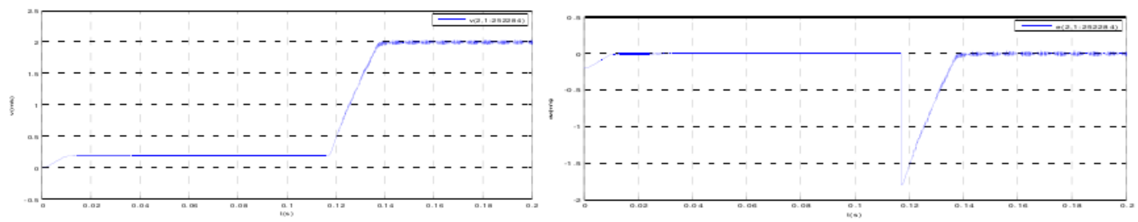
(c) Velocity waveform (d) Velocity waveform error

Figure 9 Waveform of the motor parameters with the mutation load and speed is 0.2 m/s.

3) With a rated load of the motor 50 N, when the motor speed adjusts from 0.2 m/s to 2 m/s, the parameters waveform of the motor are shown in Figure 10 (a) ~ 10 (d).



(a) Torque waveform (b) Three-phase current waveforms



(c) Velocity waveform (d) Velocity waveform error

Figure 10 Waveform of the motor parameters when When the load is 50N and velocity mutation.

As shown in figure, before the speed changes, electromagnetic torque is stable at 50N, speed reaches a given value. When the speed suddenly changed from 0.2 m/s to 2 m/s, the electromagnetic torque of the motor sudden increased and the speed is adjusted to re-stabilize at the new point near 50N. The same variation rule of three phase current and electromagnetic torque, speed suddenly increases when the current increases, and with the completion of a stable speed adjustment on the new current value, at the same times in order to satisfy the requirements of the motor speed, the current value is greater. Speed error increases when a sudden change in speed, this is because the speed must be calculated after the acquisition of the voltage and current.
At the situation of the sensorless vector control of PMLSM, two speed estimation models are respectively for simulation in low speed.

Steady state performance：Fig. 11 shows speed, torque, flux, speed error and position error between high frequency estimation and measurement under steady-state at 70 rpm.

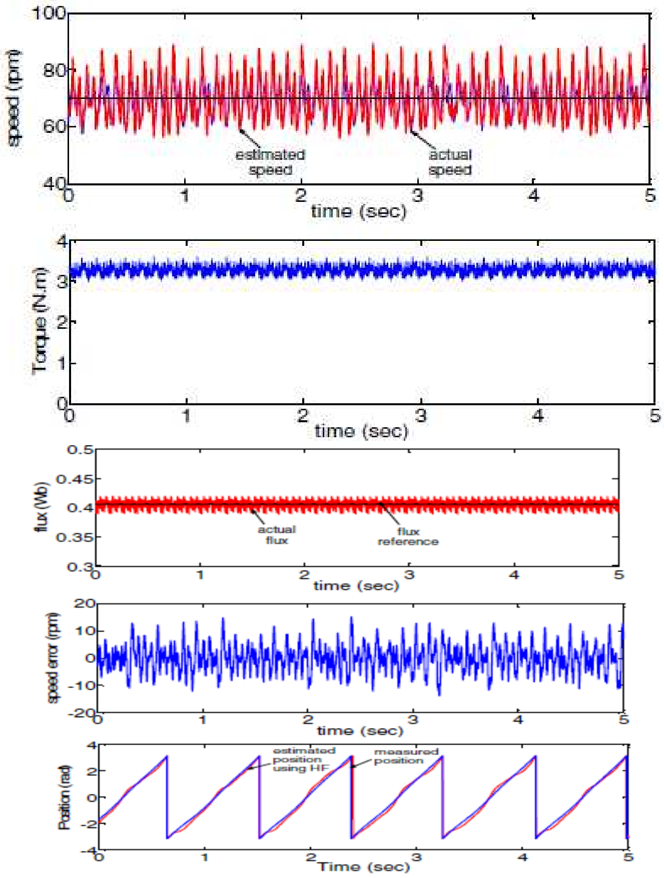
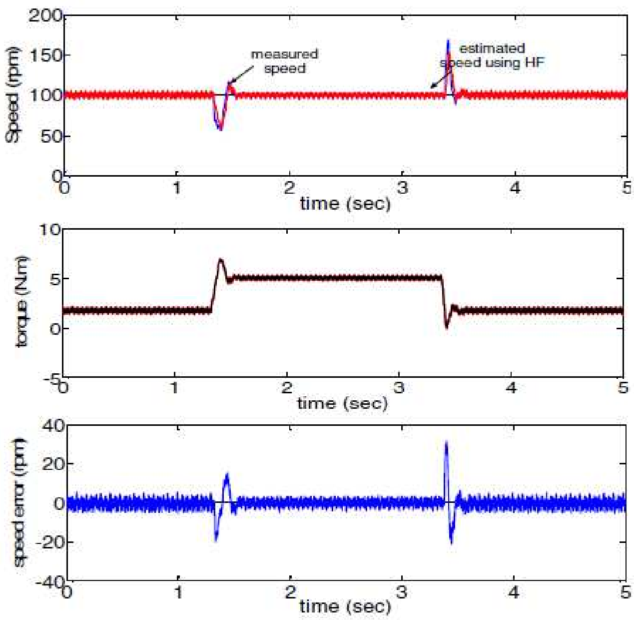


Fig11 Steady-state performance of DTC with HF injection at 70 rpm.

As can be seen from the figure, the speed error estimation position obtained from HF injection compared with the measured position is very small, confirm the effectiveness of the method at 70 rpm. However, as the effect from concentrated winding PMLSM with low saliency ratio and non-sinusoidal MMF, the estimation using high frequency injection is difficult to work at lower speeds.



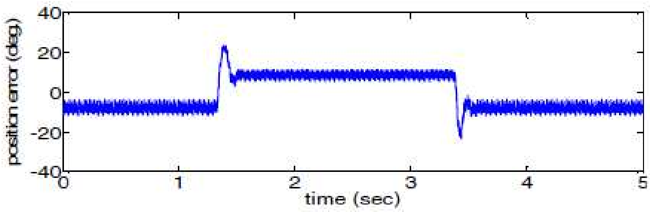


Fig12 Dynamic performance of DTC with HF injection under load Disturbance

Dynamic performance: The dynamic response of the drive to load step change is illustrated in Fig. 12. The machine initially was run at 100 rpm under no-load condition. Then load of 5 N.m was applied to the shaft of the motor at t=1.25s.

At t=3.3s, the load torque was abruptly removed and the machine come back to the no-load condition. The errors between estimated and actual speed and position are very small as shown in Fig. 12. This speed and position error indicated the good estimation performance. The ripple in the measurement results is caused by harmonics in the CW PMLSM and current measurement inaccuracies.

CONCLUSION

In this paper, an enhanced adaptive speed sensorless method is applicable to a wide range of speeds, MRSA and high frequency signal injection method are used to optimize the speed identification method comprehensively, to achieve a closed-loop start of the whole system, common in the low speed range for an accurate estimate of the PMLSM speed and improves the low-speed dynamic performance of the system. From the analysis of the simulation results, the improved adaptive speed observer under different given speed can be a real reflects of the rotor speed and position, speed and parameter mutation experiments verified it has good stability and robustness in the vector control system.
By algorithm simulation and results analysis, the MRAS and high frequency signal injection methods are proved to be available in the sensorless vector control for PMLSM, and either has its own superiority. Both methods has good stable state precision, as parameter identifications are based on the design of stability, and ensure the convergence of parameter estimation. The MRAS method is relatively simple to achieve, but the dynamic property is general, because the prerequisite for MRAS identification is that the rotor angular speed remains constant or changes slowly compared to the convergence rate at least. Hysteresis of PI adaptive controller also influences the property in dynamic process.

Acknowledgements
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