A Comparative Study on Field Oriented Control and Direct Torque Control for Permanent Magnet Linear Synchronous Motor

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Abstract—**Although the permanent magnet linear synchronous motor has been used in industry gradually, it has some drawbacks to restrict the using region. In order to overcome the disadvantages, the advanced control strategies were adopted to improve the performance of PMLSM. In the paper, the field oriented control and direct torque control strategies were researched, their control model was established respectively, so that their simulation results were given to rectify the control effects. Though the comparative analysis, it is showed that the FOC has quickly dynamic response to track the system performance although its mathematic model is more complex, the DTC also has quickly dynamic response, but its torque and flux linkage have more obvious pulsation.**

Index Terms—**comparative, field oriented control, direct torque control, permanent magnet linear synchronous motor.**

I. INTRODUCTION

As a kind of special electrical motor, the permanent magnet linear synchronous motor (PMLSM) can be seen as a permanent magnet rotating synchronous motor (PMRSM) cut along the radial and stretched the linear style, its mainly feature is direct driver function. PMLSM can connect the load and motor's mover directly constructed an integrated structure. The PMLSM direct driver system can convert the electrical energy directly into mechanical energy without any other intermediate drive gearing, so that it can eliminate the advance effects of PMRSM connected through link bar, such as backlash, high friction and high inertia etc. Because of its simple and high stiffness structure and direct driver model, the PMLSM can obtain more high speed and accelerate than the traditional PMRSM. It has a lot of advantages, such as high force density, lower inertia, high positioning precision and accuracy, high dynamic performance, unlimited travel and so on. In recent years, PMLSM has been widely used in electromechanical servo system, high speed and high precision digital control system, precision instrument, precision machining, horizontal and vertical transportation system, and other industry application region[1-3].

Meanwhile, the PMLSM drive system also have some drawbacks, its direct driver model without intermediate drive transmission make the PMLSM sensitive to internal system perturbation and external disturbances. It has some disadvantage, such as the end effect, nonlinear model and parameter uncertainty to bring the thrust ripple, slot and end effects, which can reduce the servo performance of PMLSM. The disadvantages of PMLSM make the system control more difficult, so the more high requirement was proposed to design the controller to improve the system performance of PMLSM[4-7].

The direct torque control (DTC) algorithm was proposed in 1971 in the IEEE, which were firstly applied in the mid 1980s, and then it was extended to the weak magnetic speed range. The control strategy can achieve a very quick and precise torque control response without using of complex algorithms.

In this algorithm the instantaneous values of the stator flux and torque are calculated according to the primary variables (stator currents and voltages). They can be controlled directly by selecting an optimum inverter switching table, which are used to determine the optimum voltage vector of the inverter to obtain the fastest torque control. It does not need coordinate transformation and any current regulator, the resulting DTC structure is particularly simplistic and therefore, becomes its major advantage and thus can be considered as high performance vector controllers based on the decoupling of flux and torque.

DTC has shown to be the simplest torque control of permanent magnet synchronous motor for industrial applications where torque control is highly desirable．It

requires few sensors and does not depend heavily on motor parameter estimation[8].

The first asynchronous motor high-end inverter based on direct torque control was advent in the ABB company in 1995. In recent years, the direct torque control strategy was used in electric locomotive traction system, vertical lift system and some high power AC variable speed applications. It is reported that the tram cars and electric locomotives based on DTC had reached 1000 in ABB.DTC has been widely attention and research, because it novel control ideas, clear and concise system architecture and excellent dynamic performance. Nowadays, Germany, Japanese and American are developing the DTC technology, then pushed out asynchronous motor variable frequency speed regulation device. In China, Tsinghua University, Nanjing University of Aeronautics and Astronautics and CSR have made great achievements[9-10].

Now, DTC has existed for two decades, it still has some disadvantages. The slow transient response to the step changes in torque during start-up is one of the disadvantages, which can exist in conventional DTC. The most serious disadvantage of conventional DTC is the ripple, which exists in the torque and flux variables. This undesirable ripple is of higher value when the selected state of the inverter remains unchanged for several sampling periods, which accordingly implies that the switching frequency of the inverter is not constant.

The maintaining of the inverter switching frequency constant is of course particularly important so far as the optimized design of the converter is concerned. Several techniques have been proposed to overcome this problem. These include Space Vector Modulation (SVM)[11], multilevel inverter[12], predictive control[13] and artificial intelligence technique[14-15]. But these techniques make the control scheme more complex and remove the basic advantage of DTC-simplicity[16].

The field oriented control (FOC) was proposed by F.Blaschke in the Siemens company in 1970s. FOC has two kinds of models, they are field oriented vector control based on rotor magnetic field and stator magnetic field. The field oriented control based on stator magnetic field was proposed in 1980s, it has two basic control ideas, the direct torque self-control theme by professor M.Depenbrock in Germany, another one is direct torque and flux linkage control theme by professor I.Takahashi in Japan The coordinates transformation is adopted in FOC, it makes the three phase transform to two phase perpendicular for the AC motor, so that we can control the AC motor according to the DC motor's control rules，which can control the flux linkage and torque respectively[17].

In order to overcome the shortcomings to improve the servo performance of PMLSM, we can improve the structure design of PMLSM, or adopt some advance control strategies, such as the field oriented control and direct torque control. The field oriented control (FOC) is a kind of usual control method for AC servo motor. It is being used in PMLSM controlling. According to the multivariable, nonlinearity and strong coupling of PMLSM, the field oriented control converts the stator current of PMLSM into rotor synchronous current by using vector conversion technology. That separates the flux linkage and torque currents so as to linearly control the output torque of PMLSM, so that the thrust ripple and end effect can be reduced, and the servo performance was improved for the PMLSM servo system. The direct torque control (DTC) is also a kind of advance control strategies for AC servo motor after the vector control. It is being used in PMLSM controlling. According to the multivariable, nonlinearity, strong coupling of PMLSM and avoiding the complex coordination convert of vector control, the direct torque control can direct control the torque of motor through stator flux orientation technique, converts the stator current of PMLSM into rotor synchronous current by using vector conversion technology so that the end effect and torque ripple can be reduced and the control performance can be improved of PMLSM[18-22].

The permanent magnet linear synchronous motor usually can be divided into sine wave driving permanent magnet linear synchronous motor and the square-wave driving permanent magnet Brushless DC motor. In the paper, the two control strategies FOC and DTC were researched for PMLSM driven by three phase sine wave.

II. THE MATHEMATICAL MODEL OF PMLSM

In order to establishing the accurate mathematic of PMLSM, the assumptions were given as follow [23]:

a. the primary has Symmetrical three-phase winding connected with Y, which have the same number of turns, resistance and other parameters;

b. the rotor has not damper winding, the conductivity ratio is zero for the permanent magnet materials, the magnetic circuit is linear and the effects can be ignored of hysteresis, eddy current and magnetic saturation on the motor;

c. the fundamental magnetic potential is considered, which is produced by permanent and stator winding;

d. ignored the cogging, not considering the effects on motor parameters of the temperature and frequency changing.
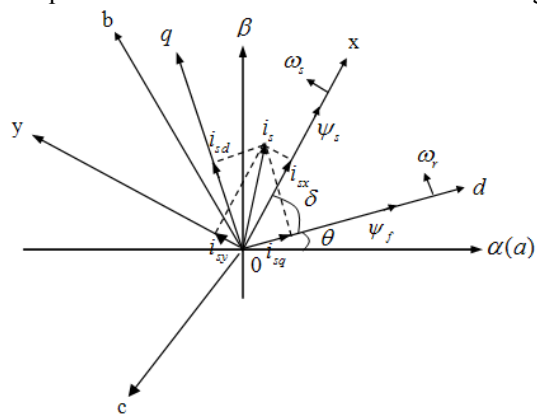
The space vector coordination for PMLSM is as Fig.1.

Figure 1. The space vector axis of PMLSM

In the Fig.1, the *abc* is three-phase static coordinates, *a*-axis points to the actual stator phase A axis, $\alpha\beta$ is two-phase static coordinates. *xy* is stator rotor coordinate, the positive direction of *x* axis is the direction of stator flux linkage of ψ_s. The torque angle δ is the angle between *x* axis and *d* axis. *dq* is two-phase rotating coordinate on the rotor, the positive direction of *d* axis is the direction of rotor flux linkage ψ_f, θ is the angle between *d* axis and *a* axis. When the load is constant, *xy* and *dq* coordinates are synchronization, that means δ is constant, conversely, δ is a variable [24].

According the assumptions and space vector coordinates, the mathematic model can be obtained based on rotor rotating *dq* coordinates system.

The equations of voltage, flux linkage, torque and motion for PMLSM are as follow:

The voltage equations are:

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

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

In the eq.(1) and eq.(2), p is differential operator, R_s is armature winding resistance, ω_r is rotor angular velocity. They show *d* and *q* components of the stator voltage in the rotor synchronous *dq0* axis.

The flux linkage equations are:

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

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

In the eq.(3) and eq.(4), ψ_f is flux linkage constant of permanent magnet, L_d and L_q are *dq* coil self-inductance.

The electromagnetic torque equation is:

$$T_e = \frac{3}{2} p_n (\psi_d i_q - \psi_q i_d) = \frac{3}{2} p_n \begin{bmatrix} \psi_f i_q + \\ (L_d - L_q) i_d i_q \end{bmatrix} . \tag{5}$$

The electromagnetic torque equation on $\alpha\beta$ coordinates is:

$$\begin{aligned} T_e &= \frac{3}{2} p_n (\psi_\alpha i_\beta - \psi_\beta i_\alpha) \\ &= p_n \frac{1}{L_s} \psi_s \psi_f \sin\delta \end{aligned} . \tag{6}$$

In the eq.(5) and eq.(6), T_e is electromagnetic torque, p_n is motor pole pairs. ψ_α and ψ_β are $\alpha\beta$ axis components of the stator flux linkage. δ is the torque angle between ψ_s and ψ_f.

The mechanical motion equation is:

$$J \frac{\omega_r}{dt} = T_e - T_L - B\omega_r . \tag{7}$$

The variable J is moment inertia, B is friction coefficient.

In the static two phase $\alpha\beta$ axis, the voltage, flux linkage and torque are as follow:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} R_s + pL_a & pL_{\alpha\beta} \\ pL_{\alpha\beta} & R_s + pL_\beta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \omega_r\psi_f \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} . \tag{8}$$

$$\psi_\alpha = \int (u_\alpha - R_s i_\alpha) dt . \tag{9}$$

$$\psi_\beta = \int (u_\beta - R_s i_\beta) dt . \tag{10}$$

$$T_e = \frac{3}{2} p_n (\psi_\alpha i_\beta - \psi_\beta i_\alpha) . \tag{11}$$

In the eq.(8), (9), (10) and (11), u_α and u_β are $\alpha\beta$ axis components of the stator voltage. i_α and i_β are the stator current $\alpha\beta$ axis components. ψ_α and ψ_β are $\alpha\beta$ axis components of the stator flux linkage.

For the vector control of PMLSM, three kinds of coordinate change are used, they are stator three phase *abc* coordinate, stator two phase static $\alpha\beta$ coordinate and two phase *dq* coordinate based on the rotating magnetic field of rotor. They have the following conversion relationship.

$$\begin{bmatrix} F_d \\ F_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} . \tag{12}$$

$$\begin{bmatrix} F_\alpha \\ F_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} . \tag{13}$$

$$\begin{bmatrix} F_d \\ F_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} F_\alpha \\ F_\beta \end{bmatrix} . \tag{14}$$

In the eq(12),(13) and (14), F can be expressed voltage, current and flux linkage respectively.

III. THE CONTROL MODEL OF PMLSM.

A. The Principle of Field Oriented Control.

The field oriented control can reduce the torque ripple, end effect and improve the dynamic response performance for the torque control research. The field

oriented strategy of PMLSM is same as PMRSM. There are some mainly control methods:

a. $i_d = 0$ control method, *b.* maximum torque-current ratio control method, *c.* $\cos\delta = 1$ and constant flux linkage control methods, etc.

The $i_d = 0$ control method is a simple and high efficient current control scheme, it doesn't have demagnetizing effect without *d* axis demagnetizing component for the armature reflect. The performance of PMLSM will not be deterioration for the demagnetizing phenomenon, so that the electromagnetic torque is proportional to the armature current. It is $T_e = p_n \psi_f i_q$, in the paper, the system principle of FOC for PMLSM based on $i_d = 0$ as Fig.2.
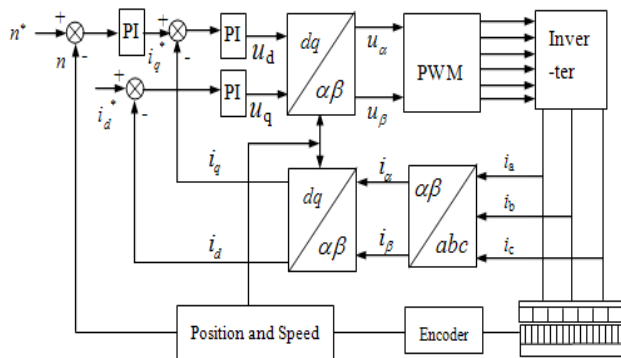

Figure 2. $i_d = 0$ FOC principle of PMLSM

The control scheme mainly contains several control modules. They are stator current detection, rotor position and speed detection, 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 is detected by using sensor, the rotor speed and electrical angle are calculated, 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. 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.

B. The Simulation Model of Field Oriented Control for PMLSM.

According to the vector control principle, the PMLSM vector control model was established based on PWM, it contains PMLSM module, the coordinate transformation and inverse transformation from stationary coordinate to synchronous rotating coordinate, speed regulator loop and current regulator loop, then a dual closed loop vector control system is built for PMLSM based on PWM control. Its simulation model as Fig.3

C. The Principle of Direct Torque Control

The classical bang-bang control was adopted for the PMLSM direct torque control, as Fig.4. The stator flux
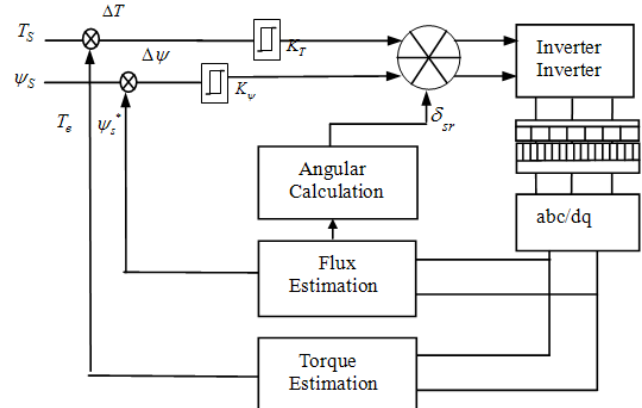

Figure 4. Direct torque bang-bang hysteresis loop control principle

linkage and torque observe model were established for PMLSM. According to the stator voltage u_s and rotor position signal δ_{sr}, the electromagnetic torque T_e and
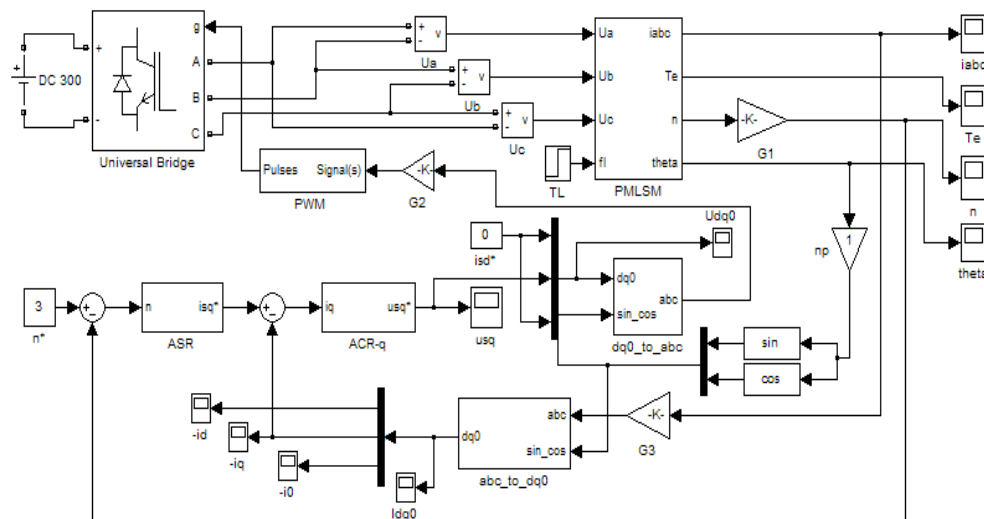

Figure 3. The field oriented control simulation model of PMLSM.

Figure 5 Note how the caption is centered in the column.

stator flux linkage ψ_s on the static coordinates were estimated. The controller is contained the stator flux linkage, motor torque and speed variable, the setting speed and stator flux linkage amplitude. The direct control was realized through the flux and torque control signal and the real position signal of torque angle. According to the flux, torque variable quantity and torque angle, the proper switch signal was inquired to control the inverter to drive the PMLSM.

D. The Experiment Simulation of Direct Torque Control

According to the vector control principle, the PMLSM vector control model was established based on PWM, it contains PMLSM module, the coordinate transformation and inverse transformation from stationary coordinate to synchronous rotating coordinate, speed regulator loop and current regulator loop, then a dual closed loop vector control system is built for PMLSM based on PWM control. Its simulation model as Fig.5

IV. THE SIMULATION EXPERIMENT OF PMLSM.

A. The Simulation Experiment of Field Oriented Control for PMLSM

The field oriented control of PMLSM based on PWM 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 0.2324Wb, rotor resistance R_s is 1 Ω, d axis inductance L_d is 13.91mh, q axis inductance L_q is 13.91mh, viscous friction coefficient B is 0.1N • s/m, rotor mass is 96kg, pole pitch τ is 39mm.

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, after 0.5s, then the variable state of speed, torque, stator abc axis current and dq axis current can be obtained along the whole loading

process, their response state respectively as Fig.6, Fig.7, Fig.8 and Fig.9.

Although the simulation experience results have some overshoot, the response of speed and torque are very quickly, they can recover the setting variety in time and reduce the ripple successfully when the PMLSM is starting and changing the load. It is showed that the vector control can provide greatly dynamic performance for PMLSM in Fig.6 and Fig.7.

Figure 6. Speed response of PMLSM.

Figure 7. Torque response of PMLSM.

In Fig.8 and Fig.9, we can see the stator current at static *abc* coordination and synchronous rotating $\alpha\beta$ coordination respectively. It is showed that the *q* axis current component can separate successfully, so that we can control the speed and torque directly and obtain perfectly dynamic performance for the PMLSM through vector control.
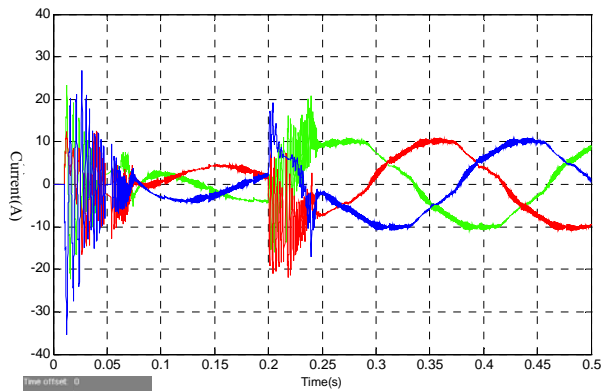
Figure 8. Stator *abc* axis current
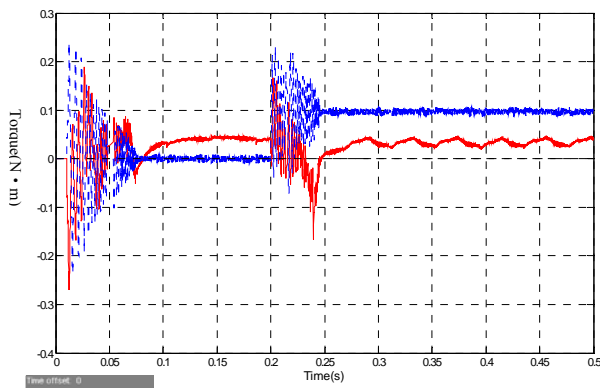
Figure 9. Stator *dq* axis.currrent

B. The Simulation Experiment of Direct Torque Control

The direct torque control of PMLSM based on bang-bang control can be verified through the experiment simulation. The system simulation parameters are given as parameters in simulation A.

In the experiment, the given load torque was 1000N • M and speed was 3.0m/s, at 0.2s the load torque was changed as 1000*N • M*, after 0.5s, then the variable state of flux linkage, speed and torque can be obtained along the whole loading process, their response state respectively as Fig.10, Fig.11 and Fig.12.

In the Fig.10, it showed that the state flux trajectory of DTC for PMLSM is almost circle although it has some period fluctuation, it is mean that the ideal state flux linkage trajectory can be obtained though the direct torque control.
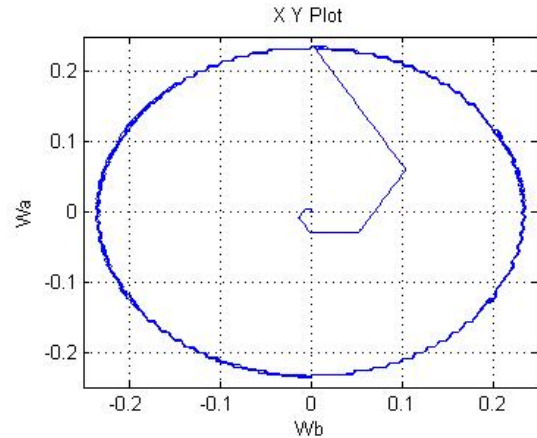

Figure 10. The flux linkage of DTC for PMLSM

From the Fig.11 and Fig.12, although the response has a certain overshoot, it shows that the speed and torque response are very quickly. At 0.2s, the load was changed suddenly, it has some ripple, the response can track the setting variable in time, and the ripple of torque is very little.
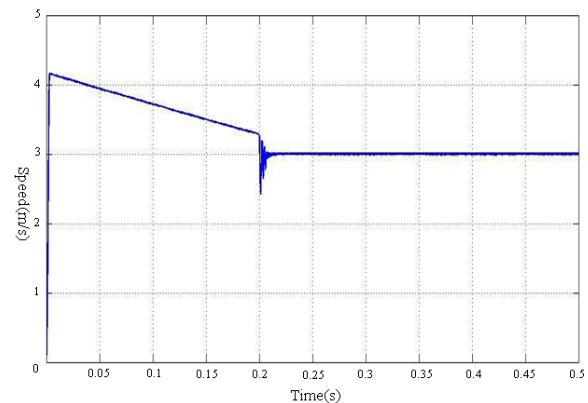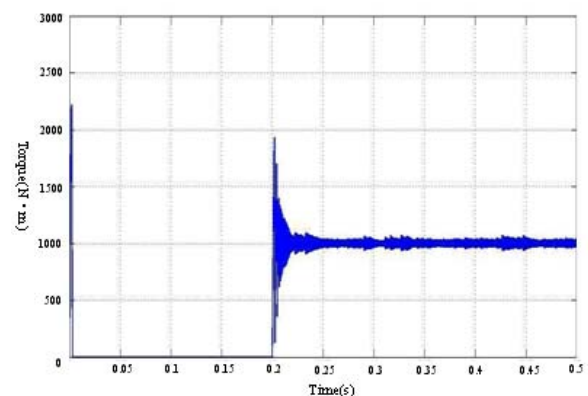

Figure 11. Speed response of PMLSM

Figure 12. Speed response of PMLSM

IV. RESULTS AND DISCUSSION

In this paper, a vector control model based on PWM for PMLSM has been proposed. The detailed vector controller model for PMLSM is given, and the $i_d = 0$

vector control method was simulated. It is known that the proposed method can separated the q axis current component accurately through abc/dq coordinate transformation, and control the electromagnetic torque directly without the effect of d axis component. From the experiment, although the speed and torque had some ripple when the load was changing, it is seen that the speed and toque can be followed perfectly. With the vector control scheme of PMLSM, it shows that the flux and torque ripples can be reduced obviously, the PMLSM drive system still keep the quick dynamic response characteristic. The classical direct torque control based on bang-bang control was established and simulation. The whole control structure and experiment simulation model was given. It is showed that direct torque control based on bang-bang has simple structure without complex coordinates convert. From the simulation experiment, it is known that the DTC has quick dynamic response and low flux and torque ripples. The DTC can improve the performance of PMLSM, which is benefit for the PMLSM used in precision machine and accuracy position servo system. It is showed that the two control strategies all have the quickly response advantage, but all have the disadvantages respectively, the former has complex coordinate transformation, the latter has more obvious pulsation.

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