Iterative Learning Based Thrust Ripple Suppression for PMLSM

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Abstract

A fuzzy-PID-based control strategy was provided to deal with thrust ripple of multi-segment primary Permanent Magnet Linear Synchronous Motor. First these thrust ripple suppression model is proposed. The iterative learning algorithm is then synthesized with the velocity regulation for current compensation. Simulation results verify the strong suppression of thrust ripple even with periodic disturbances.

Keywords: multi-segment primary Permanent Magnet Linear Synchronous Motor, thrust ripple, iterative learning control, feedforward compensation.

1. Introduction

PMLSM vertical hoisting system consists of multi-segment primary armature windings, rotor and lifting container. Primary armature windings are evenly placed in the fixed frame (hoist Guide); the no-salient pole type rotor consists of permanent magnet and the rest. The car platform moves vertically with the rotor. Without the trouble of mechanical transmission device it employs the segmented power supply mode and does not need any electricity in the whole process, it is energy -saving, and efficient. Due to its significant economic and social benefits, more and more attention is being paid to PMLSM. However, in the actual operation process, the permanent magnet will be disturbed inevitably, if the disturbance can not be solved in time, it will make the system run out of synchronization, the rotor and cage motor will decline dramatically due to the gravity, causing serious accidents. Therefore, the application of new control strategy is necessary to limit the force ripple and avoid the accident.

Many experts and scholars have done a lot of work in the thrust fluctuation suppression of linear motor. Their methods can be grouped into two kinds: One is to reduce the force ripple by optimizing the motor structure. The other is to compensate and restrain the force ripple by algorithmic control.

Based on its characteristics, this paper builds the mold of force ripple for PMLSM. It realizes the advanced control of the force ripple through the feedforward compensation of PMLSM.

2. The basic structure and working principle of segmented PMLSM hoisting system

As shown in figure 1, the segmented PMLSM hoisting system uses the double hidden pole. By rolling pulley, it moves up and down on the track. The length of the track of the rotor is equal to the total length of the table and the longitudinal length of the interval so as to make the coupling field area of the primary and the permanent magnet unchanged in the process of longitudinal motion of the rotor.

The air gap magnetic field will be generated when the three-phase windings of PMLSM are connected to the three sine alternating current. If the longitudinal end effect caused by the opening of the two ends is not considered, the air gap magnetic field can be regarded as the sine wave distributed along the straight line. When the three-phase current changes with time, the air gap magnetic field will move along a straight line in the sequence of A、B、C (or A、C、B) , which is called the travelling magnetic field. The interaction of permanent magnet magnetic field and the travelling magnetic field generated by the armature winding will produce electromagnetic force. With the force, the rotor will do linear movement along the direction of the travelling magnetic field because of the fixed stator armature winding Group.

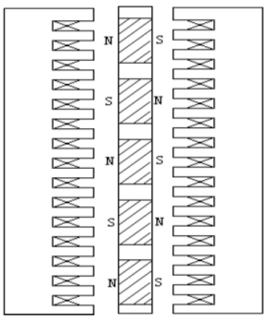

Fig.1 Double-side non-salient pole PMLSM

3. The analysis of segmented permanent magnet linear motor

The thrust wave is generated in the process of the segmented permanent magnet linear synchronous motor. The main reasons of the production of thrust fluctuation are: the breaking of the end core, which produces the unique end effect of the linear motor, that is, the force of the end, the differences of magnetic permeance between the core and the groove produce the cogging effect, which is the same as that in rotary motor. That is cogging force; the frequent transformation of the motor stator armature winding during the operation will change the parameters of the motor caused by the change of the air gap.

The equation for the thrust is:

$$F(t) = ki_q(t) \tag{1}$$

$$F(t) = M\ddot{x} + f_s(t) + f_m(\dot{x}) + f_g(x) + f_q(t) \tag{2}$$

In the above equations： $F(t)$ is the thrust, $f_s(t)$ is the carrying capacity, $f_m(x)$ is force of friction, $f_g(x)$ is ripple thrust, and $f_q(t)$ is other disturbance. Since the Double-side non-salient pole mode is adopted, the force of friction is ignored in this study; x is the position of the motor.

The ripple thrust caused by frequent switching of the motor stator armature winding and the uneven density of the air-gap field caused by slot effect and end effect bear direct relationship with the motion position of the permanent linear motor. And the mathematical model for the ripple thrust is:

$$\begin{aligned} f_g(x) &= A_g \sin(wx + \varphi) \\ &= A_{g1}\cos wx + A_{g2}\sin wx \end{aligned} \tag{3}$$

In formula (3), A_g is the amplitude of the ripple thrust; A_{g1} and A_{g2} are the constants; w is the angular velocity of the constant displacement; φ is the initial phase angle. $A_g, A_{g1}, A_{g2}, w, \varphi$ are all related to the structure of the linear motor.

4. Suppression strategy of force ripple of segmented permanent magnet synchronous motor

Force ripple Suppression strategy principle control is shown in figure2. The systematical control includes a master controller and a feedforward controller based on iterative learning control. Influenced by the force ripple caused by the side effect of the linear motor, the controlling effect would not be good if the master controller is applied. Therefore, iterative learning controller is used to predict the force ripple and compensate the main control system so as to reduce the influence of the force ripple on the performance of the linear motor control.

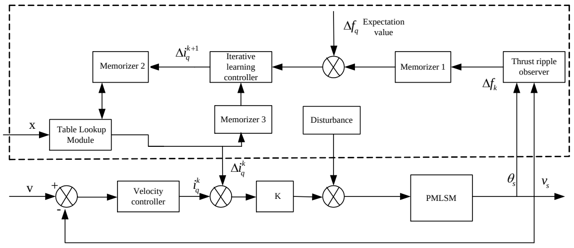

Fig.2 Iterative learning based thrust ripple suppression diagram for PMLSM

4.1. *Force ripple observer*

The working principle of the force ripple observer is as following: according to the actual position and the speed of the linear motor, it can calculate the thrust of the push and then put it into the memory, and then to the Iterative learning controller.

According to the analysis of force angle characteristics of permanent magnet linear motor, the relationship of the speed between thrust power and Angular (position) can be obtained.

$$F(t) = \frac{3E_0 U_s}{\upsilon Z}\sin(\theta+\alpha) - \frac{3{E_0}^2 R_s}{\upsilon Z^2} \tag{4}$$

$$\theta = \frac{\pi}{\tau}x - \omega t = \frac{\pi}{\tau}x - \frac{\pi}{\tau}\upsilon t \tag{5}$$

$$\Delta f_k = k i_q^*(t) - \frac{3E_0 U_s}{\upsilon_k Z}\sin(\frac{\pi}{\tau}x_k - \frac{\pi}{\tau}\upsilon_k t) + \frac{3{E_0}^2 R_s}{\upsilon_k Z^2} \tag{6}$$

In formula (4),(5) and (6), $\alpha = \arctan R_s / X_T$, Δf_k is the dynamic thrust after K times iteration; $i_q^*(t)$ is the given electric current; x_k and υ_k are position and speed after k times iteration; Z is the synchronous impedance, E_0 is the no-load electric potential of the motor, U_s is the imposed voltage on the linear motor stator armature winding.

4.2. *Iterative learning controller*

Through the formula 3, it can be seen that there is a direct relationship between the ripple thrust and the position (time) of the permanent magnet linear motor. When the vertical motion of the linear motor is repeated, the relationship between the ripple thrust and the position (time) of the permanent magnet linear motor remains the same. Therefore, this paper uses an iterative learning controller to compensate for the ripple thrust and eliminate the thrust fluctuation.

The operation principle of the iterative learning controller is as following: after k times iteration and before the next target position, the controller finds out the offset current in Memory 2 via lookup table. And linear motor, compensates the thrust ripple and stores then it will send the current to the major loop of the Δi_q^k in Memory 3; Afterwards it will store Δf_k sent by thrust observer in Memory 1 and learn $\Delta i_q^k(t)$ in Memory 3 and the difference value between the controller-predicted thrust ripple Δf_k and expected thrust ripple Δf_q , namely, $e_k(t) = \Delta f_k - \Delta f_q$. As the offset current after k+1 times iteration, the newly obtained offset current $\Delta i_q^{k+1}(t)$ will do the above operations again and realize feedforward compensation effect.

The learning scheme is the iterative learning control scheme. This paper uses PID as the learning scheme, namely, the last control information and current errors are used as correction terms.

Applied in study, the designed learning scheme of the iterative learning is:

$$\Delta i_q^{k+1}(t) = \Delta i_q^k(t) + \Gamma_p e_k(t) + \Gamma_i \int_0^t e_k(\tau)d\tau + \Gamma_D \frac{de_k(t)}{dt} \tag{7}$$

Repeated interactive learning results in thrust ripple approaching zero as close as possible.

5. Simulink Simulation

In order to analyze the control effect of the controller designed in this paper, the iterative learning based thrust ripple suppression system for PMLSM is simulated through the platform of Matlab or Simulink, and a disturbing force with its amplitude and mean at 6N is added according to the actual interference condition of the linear motion actuator.

The parameters of the permanent magnet linear motor are set as follows : the weight of the active cell is 20kg; the number of the active cell pole- pairs is 2;

the polar distance of permanent magnet is 30mm, the thrust coefficient is 11.45N/A; the armature resistance of the active cell is 1.30Ω; and its inductance is 5.30mH with coefficient potential as 1.05×10^{-3} (Wb.s)/m.

The following result is concluded from the stimulation:

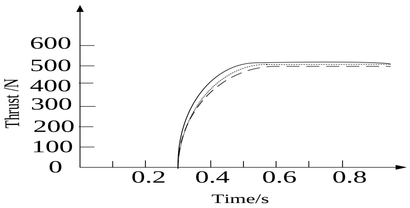

Fig.3 The thrust curve under different iteration times

From figure.3 it is loaded at 0.3s.The solid line is the given thrust curve, the dense dotted line is the thrust curve after 20 times iteration and the sparse dotted line is it after 10 times iteration.

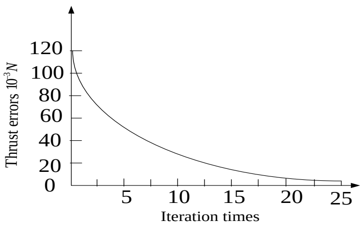

Fig.4 Maximum thrust error under different iteration times

From figure.5, the maximum thrust error after 10 times iteration is 40×10^{-3}N, which is reduced to10×10^{-3} N after 20 times iteration. So more iterations can reduce the thrust error.

6. Conclusions

(1)This paper employs the control strategy of a combination of the iterative learning controller and the thrust fluctuation observer to control the thrust fluctuation in advance.

(2)The thrust fluctuation compensation strategy takes the impact of the thrust fluctuations into consideration.

The results of the simulation show that the control strategy has strong power to suppress the thrust fluctuation so as to improve the stability of the linear motor.

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