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Single neuron network PI control of high reliability linear induction motor for Maglev*

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Abstract: The paper deals with a new model of linear induction motor (LIM) to improve the reliability of the system. Based on the normal equation circuit of LIM considering the dynamic end effect, an equivalent circuit model with compensation of large end effect is constructed when the end effect force at synchronism is of braking character. The equivalent circuit model is used for secondary-flux oriented control of LIM. Single neuron network PI unit for LIM servo-drive is also discussed. The effectiveness of mathematical model for drive control is verified by simulations.

Key words: Linear induction motor (LIM), Field-oriented control, End effect
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INTRODUCTION

The linear inductance motor (LIM) is used in such low-speed Maglev system as HSST system to drive vehicles (Wu, 2003). LIM has the end effect owing to its unique configuration. The eddy current produced by the dynamic end effect causes additional loss of linear motor which reduces thrust (Duncan and Eng, 1983; Boldea and Nasar, 1999). When the vector control strategy is applied to LIM, the influence of the end effect must be considered and an exact mathematical model should be constituted to improve the whole performance of the control system.

In this paper, the equation circuit of LIM considering large end effect is discussed, and the calculation model of LIM is deduced. The intelligent control method is adopted to solve the problem of robustness. The single neuron control PI unit is adopted for LIM servo-drive because of its simple configuration. The simulation has validated the obvious effects of those methods on improving the whole performance, including reliability.

EQUATION CIRCUIT OF LIM CONSIDERING END EFFECT

In a long secondary type LIM, as the primary moves, the secondary is continuously replaced by new material. This new part material tends to resist a sudden increase in flux penetration and only allows a gradual buildup of the flux density in air gap. Eddy current in the entry or exit end of secondary plate will be produced because of a sudden change of magnetic flux. This inductive current will prevent the change of air gap magnetic field (Sung and Nam, 1999).

Considering the dynamic end effect, the effective length of linear motor' primary is supposed as l, and the secondary parameter is converted into the primary's. At the entry end of secondary core, the eddy current increases promptly, and the increasing rate can be decided by $T_1=L_{r1}/R_r$ (L_{r1} is the secondary leaking inductance converted into the primary's, R_r is the secondary equivalent resistance converted into the

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primary's).

Because $T_1=L_{r1}/R_r$ is very small and can be neglected, the secondary eddy current can reach the primary exciting current I_m rapidly, while the phase of eddy current is contrary with primary current. The time constant of secondary eddy current decrease can be described as $T_2=(L_m+L_{r1})/R_r=L_r/R_r$ (L_m is the mutual inductance of LIM). At the exit of secondary plate, the eddy current increases to I_m promptly, and then decreases with the time constant T_1. The transient process is shown in Fig.1. Based on the above analysis, the end effect can be added into the equivalent circuit.

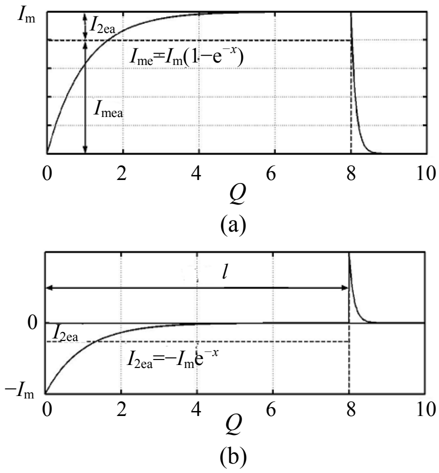

Fig.1 (a) Air gap magnetic motive force; (b) Secondary plate magnetic motive force

The relative velocity between the primary and secondary decides the distribution of magnetic flux along air gap. Suppose v is the primary velocity, in T_2 time the primary moves a length of vT_2. The time of the primary passing a point on the secondary is

$$T_v=l/v. \tag{1}$$

Then normalize the motor length

$$Q=l/(vT_2)=vT_v/(vT_2)=T_v/T_2=lR_r/[(L_m+L_{r1})v], \tag{2}$$

where Q is a dimensionless parameter representing the motor length on the normalized time scale. The average value of secondary eddy current is

$$I_{2ea}=\frac{I_m}{Q}\int_0^Q e^{-x}dx=I_m\frac{1-e^{-Q}}{Q}. \tag{3}$$

Equivalent exciting current is

$$I_{mea}=I_m-I_{2ea}=I_m\left\{1-(1-e^{-Q})/Q\right\}, \tag{4}$$

where I_{mea} is the equivalent exciting current considering the dynamic end effect. The demagnetizing effect can be reflected by amending the exciting current, so the total exciting current is

$$L_m\left\{1-(1-e^{-Q})/Q\right\}. \tag{5}$$

The virtual value of the secondary eddy current at entry is

$$I_{2er}=\sqrt{\frac{I_m^2}{Q}\int_0^Q e^{-2x}dx}=I_m\sqrt{\frac{1-e^{-2Q}}{2Q}}. \tag{6}$$

The eddy current loss at entry end is

$$P_{entry}=I_{2er}^2R_r=I_m^2R_r\frac{1-e^{-2Q}}{2Q}. \tag{7}$$

The eddy current loss at exit end is

$$P_{exit}=\frac{L_rI_m^2(1-e^{-Q})}{2T_v}=I_m^2R_r\frac{(1-e^{-Q})^2}{2Q}. \tag{8}$$

The total loss of the secondary is

$$P_{eddy}=P_{entry}+P_{exit}=I_m^2R_r(1-e^{-Q})/Q. \tag{9}$$

The eddy current loss can be described as a series resistance ($R_r(1-e^{-Q})/Q$) in exciting circuit.

Suppose $f(Q)=(1-e^{-Q})/Q$, the T-type equivalent circuit considered the end effect is shown in Fig.2.

MODEL OF LIM CONSIDERING END EFFECT

In the secondary-flux oriented vector control, the synchronous reference frame is aligned to the secondary-flux. There is no component along the q axis, $\psi_{rd}=\psi_2$, $\psi_{rq}=0$. Based on above analysis, the LIM model is described as follows:

$$u_{sd}=R_si_{sd}+R_rf(Q)(i_{sd}+i_{rd})+\frac{d\psi_{sd}}{dt}-\frac{\tau}{\pi}v_1\psi_{sq}, \tag{10}$$

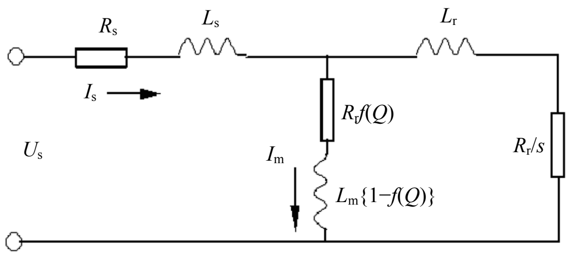

Fig.2 Equivalent circuit for LIM

$$u_{sq}=R_s i_{sq}+\frac{d\psi_{sq}}{dt}+\frac{\tau}{\pi}v_1\psi_{sd}, \tag{11}$$

$$0=R_r i_{rd}+R_r f(Q)(i_{sd}+i_{rd})+\frac{d\psi_{rd}}{dt}, \tag{12}$$

$$0=R_r i_{rq}+\frac{\tau}{\pi}(v_1-v_r)\psi_{rd}, \tag{13}$$

$$\psi_{sd}=(L_s-L_m f(Q))i_{sd}+L_m(1-f(Q))i_{rd}, \tag{14}$$

$$\psi_{sq}=L_s i_{sq}+L_m i_{rq}, \tag{15}$$

$$\psi_{rd}=L_m(1-f(Q))i_{sd}+(L_r-L_m f(Q))i_{rd}, \tag{16}$$

$$0=L_m i_{sq}+L_r i_{rq}, \tag{17}$$

$$F_e=\frac{3\pi}{2\tau}(\psi_{sd}i_{sq}-\psi_{sq}i_{sd}), \tag{18}$$

$$F_e=\frac{3\pi}{2\tau}\frac{L_m(1-f(Q))}{L_r-L_m f(Q)}\left(\psi_{rd}i_{sq}-\frac{L_{r1}^2}{L_r}\frac{f(Q)}{1-f(Q)}i_{sq}i_{sd}\right). \tag{19}$$

The second term in Eq.(19) acts as dynamic brake force caused by end effect.

SINGLE NEURON NETWORK PI UNIT

It is very important to reduce the parameter deviation of LIM model for servo-drive system. The intelligent control method has been adopted to solve the problem of robustness. The single neuron control PI unit is adopted for speed control because of its simple configuration (Ye, 2000).

Since the leaking magnetic flux in LIM is quite large for its wide air gap, it is difficult to have an accurate model of LIM. It is useful to introduce the artificial neural networks into the LIM servo-control, where the single neuron control is more practical. The configuration of single neuron is shown in Fig.3. The input of single neuron is

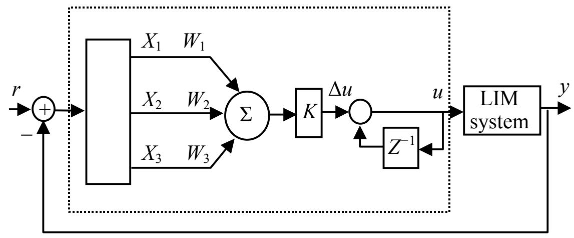

Fig.3 Single neuron control PI unit

$$\begin{aligned}&x_1(k)=r(k)-y(k)=e(k),\\&x_2(k)=e(k)-e(k-1)=\Delta e(k),\\&x_3(k)=e(k)-2e(k-1)+e(k-2),\end{aligned} \tag{20}$$

where $x_i(k)$ (i=1, 2, 3) stand for integral unit, proportional unit and differential unit of normal PID adjustor.

The output of controller is

$$u(k)=u(k-1)+K\left[\sum_{i=1}^{3}\omega_i(k)x_i(k)\Big/\sum_{i=1}^{3}|\omega_i(k)|\right], \tag{21}$$

where $|u(k)|\le U_{max}$, U_{max} is the maximum of limitation, equal to the maximum given pull of linear motor. The weight factor is

$$\omega_i(k+1)=\omega_i(k)+\eta_i r_i(k), \tag{22}$$

where $r_i(k)=e(k)u(k)x_i(k)$.

Fig.4 shows the block diagram of secondary-flux oriented control model, which consists of a LIM (Takahashi and Ide, 1993), a speed feedback control loop with single neuron control PI unit, a PWM voltage source translator, and vector control translation components.

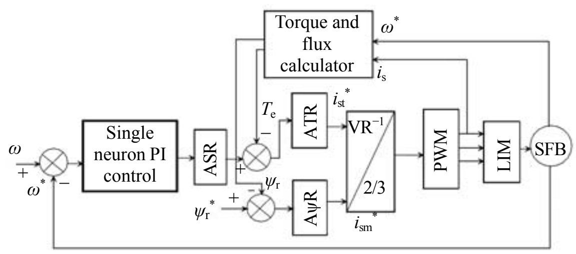

Fig.4 Secondary-flux oriented control model with single neuron control PI unit

ASR: Speed regulator; ATR: Torque regulator; AψR: Flux regulator; SFB: Speed feedback unit

RESULTS AND CONCLUSIONS

Based on the above analysis of mathematics model and control arithmetic, a simulation for LIM is performed. Comparison between single neuron PI adjustment and normal PI adjustment has been performed. The LIM used in the serve system is three-phase Y-connected two-pole 2.5 kW 50 Hz 380 V type. The parameters of LIM are: R_s=4.097 Ω, R_r=8.8 Ω, L_s=0.1002 H, L_m=0.0771 H, L_r=0.08 H, τ=0.063 m.

Fig.5 presents simulation result by LIM model discussed above.

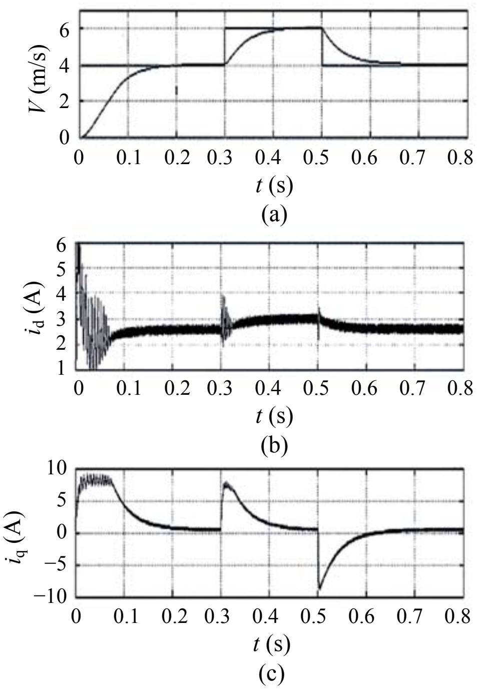

Fig.5 Simulation results. (a) Speed; (b) Current i_d; (c) Current i_q

Fig.6 shows the comparison of speed tracking with normal PI unit and single neuron network PI unit. From the simulation, it can be concluded that the speed response of the single neuron network PI adjustment is fast, and the steady-state error is smaller. For step response, the speed fluctuation is small.

In this paper, an equation circuit considering the dynamic end effect of LIM is discussed, which is suitable for the large end effect condition. The model for vector control has been presented. Single neuron network PI unit is introduced for LIM servo-drive. The simulative conclusion shows that the end effect can be compensated by this model, and the control system performance is improved. The single neuron network PI unit is suitable for the control arithmetic design.

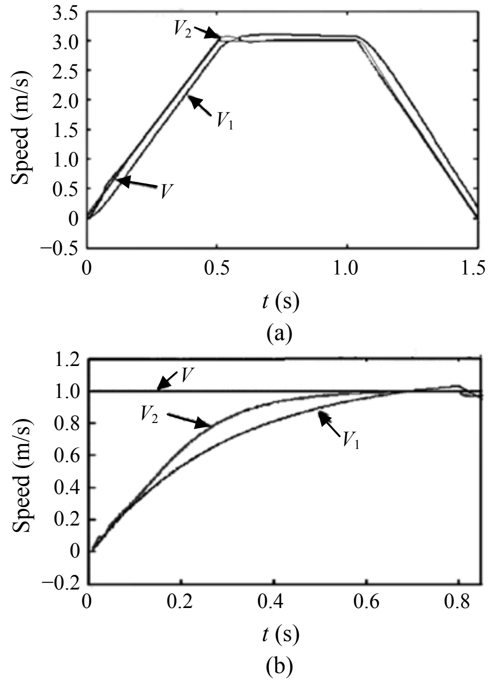

Fig.6 Speed curve for step condition

V: Set up speed; V_1: Trace speed with PI unit; V_2: Trace speed with single neuron network PI unit

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