An Operating Characteristics by the Direct Thrust Control of Single-sided Linear Induction Motor in Conveyance System

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Abstract - **In this paper, the direct thrust control of PWM Inverter-fed Single-sided Linear Induction Motor (hereinafter referred to as "SLIM") is achieved with Space Vector control and PI control. The trembling of air gap length which is occured between the primary winding core and the secondaty structure of the SLIM must be minimized in order to get quick response characteristic. First, voltage equations of SLIM are shown on the suitable d-q axis equivalent circuits which analyze characteristics of the thrust and the normal force. Also, modeling and analysis of the d-q axis equivalent circuits are able to make robust transient thrust from the current regulation in the equivalent circuits.**

These results exemplified the direct drive of SLIM with the reference speed and thrust were verified by the experiments.

1. INTRODUCTION

A LIM, which occur linear thrust force using the moving magnetic, has been steadily developed since a basic principle of LIM by the Pole-by-Pole Model was introduced. It is assumed that the secondary poles are independant but mutually coupled, the secondary winding function for each pole of the machine is sinusoidal, and the end-effect of it was represented analytically by additional secondary poles by T. A. Nordahl and D.W. Novotny in 1979[1-3]. In the research and development of LIM, a major purpose has been so far put on its operation in the high speed range.

Recently, the LIMs have quick response to rapid accelation and deceleration in the precise velocity and positioning controls by utilizing the best techniques of power electronics and the linear sensor, and have simple structures which enabled direct drive. So, these applications of LIMs have enabled the development of the new moving types of conveyance systems never realized before, and it has contributed very much to the improvement of production technologies. In conveyance systems of manufacturing line, The soft start/stop of mover is indispensable to carry out without operating shock.

And the operation of the system has weakness point when the conveyer is transferring the goods to which are subject accelerating forces. Therefore, this kind of shortcoming ought to be considered during the designing a control strategy. The trembling of air gap length, which is occurred by the primary winding core and the secondary structure, causes the thrust ripple, it is difficult to precisely control the speed of SLIM because of the bad influence of this thrust ripple. So, we have studied that the thrust control by Space Vector control[4] and PI control on the PWM Inverter-fed system was applied to the SLIM driving in order to obtain quick response for mover without trembling in air gap. The experiment machine has single-sided, short-primary-type, long-secondary-type, three-phase and 4 poles.

In conveyance SLIM, it is important to make equivalent circuits exactly to investigate operating characteristics of the SLIM to which ignored the end-effect in a low speed. These equivalent circuits are expressed d-q equivalent circuits to solve the thrust and the normal force characteristics as a function of velocity. Also, the q-axis current is separated by vector control, and it is controlled to obtain the quick response and the precise position control by the PI controller, and Space Vector Modulation is used to get the constant velocity characteristic without thrust ripple.

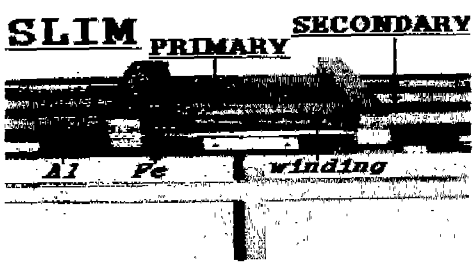
These results show to be truth with the simulations and the experiments.

2. ANALYSIS OF SLIM

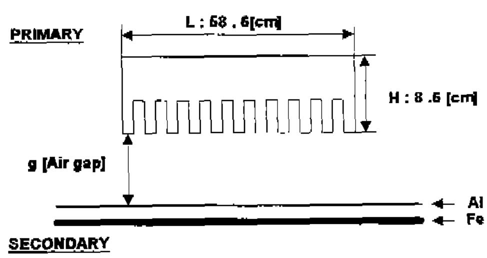
A. Equivalent circuit

Fig. 1(a), (b) show the cross section and the experiment of the testing device of conveyance SLIM used in the poposed system. And the secondary made with the Aluminium and added back iron which constructed to Fe. This construction has been important role to restraint a thrust reduction and an increase of the reluctance from the secondary.

The d-q axis equivalent circuits of conveyance SLIM proposed as the Fig. 1 are shown in as Fig. 2(a), (b).

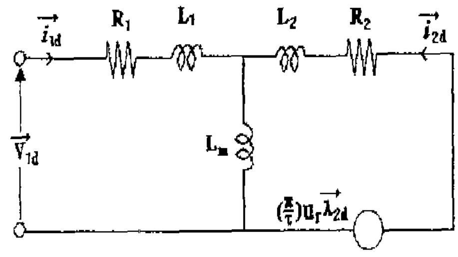


(a)Experiment machine

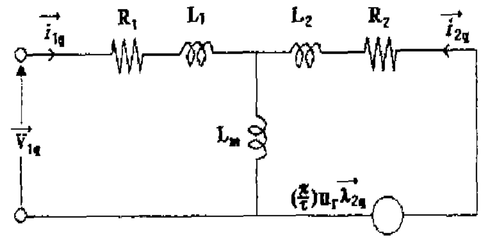


(b)Cross section

Fig. 1 SLIM(Single-sided Linear Induction Motor)



(a) d axis



(b) q axis

Fig. 2 Equivalent circuit of SLIM

From the equivalent circuits of Fig. 2, the voltage equations of the primary and the secondary of the SLIM, and its d-q axis coordinate conversion are given as following,

$$\vec{V}_{1d} = R_1 \cdot \vec{i}_{1d} + p\,\vec{\lambda}_{1d} \quad (1)$$

$$\vec{V}_{1q} = R_1 \cdot \vec{i}_{q} + p\,\vec{\lambda}_{q}$$

$$0 = R_2 \cdot \vec{i}_{2d} + p\vec{\lambda}_{2d} - j(\frac{\pi}{\tau})u_r\,\vec{\lambda}_{2d}$$

$$0 = R_2 \cdot \vec{i}_{2q} + p\vec{\lambda}_{2q} - j(\frac{\pi}{\tau})u_r\,\vec{\lambda}_{2q}$$

where, the flux linkage of the primary and the secondary are given as following,

$$\vec{\lambda}_{1d} = L_1\vec{i}_{1d} + L_m\vec{i}_{2d} \quad (2)$$

$$\vec{\lambda}_{1q} = L_1\vec{i}_{1q} + L_m\vec{i}_{2q}$$

$$\vec{\lambda}_{2d} = L_2\vec{i}_{2d} + L_m\vec{i}_{1d}$$

$$\vec{\lambda}_{2d} = L_2\vec{i}_{2d} + L_m\vec{i}_{1d}$$

The voltage equation by the d-q axis is expressed as

$$V_{dq} = R_{dq}i_{dq} + L_{dq}i_{dq} + G_{dq}i_{dq} \quad (3)$$

From Eq. (3), input power of SLIM is given as following,

$$P_{in} = i_{dq}^T R_{dq} i_{dq} + i_{dq}^T pL_{dq} i_{dq} + i_{dq}^T G_{dq} i_{dq}$$
$$= P_R + P_L + P_G \quad (4)$$

where, R_{dq}, L_{dq}, G_{dq} are each equivalent resistance term, equivalent stored energy term and equivalent energy conversion term which are separated from d-q axis equivalent circuits and copper loss power is P_R, excitation power is P_L, velocity e.m.f is P_G, and these values are writtem as following.

$$P_R = R_1(i_{1q}^2 + i_{1d}^2) + R_2(i_{2q}^2 + i_{2d}^2)$$

$$P_L = \frac{p}{2}(i_{dq}^T L_{dq} i_{dq})$$

$$P_G = \frac{\pi}{\tau} u_r L_m (i_{2d} i_{1q} - i_{2q} i_{1d})$$

where, from the excitation power P_L, velocity e.m.f P_G, we would be got the normal force and the trust force of the SLIM.

B. Normal force

The effective magnetizing power P_M and the normal power P_N was derived from the excitation power P_L. And the effective magnetizing power P_M is expressed as Eq. (6).

$$P_L = P_M + P_N \quad (5)$$

$$P_M = \frac{p}{2}(L_1(i_{1q}^2 + i_{1d}^2) + L_2(i_{2q}^2 + i_{2d}^2) + L_m(i_{1q} i_{2q} + i_{1d} i_{2d})) \quad (6)$$

According to the fluctuation of the instantaneous air gap width, the normal power P_N alternate with the normal force F_N by the differential air gap dg_e/dt.

where, the normal force F_N is the sum of the attraction force F_{na} 'and the repulsion force F_{nr} as following,

$$F_N = F_{na} + F_{nr} \quad (7)$$

The attraction force F_{na} and the repulsion force F_{nr} that occurred by the linear motor are given as following,

$$F_{na} = (i_{1q}^2 \frac{\partial L_1}{\partial g_e} + i_{1d}^2 \frac{\partial L_1}{\partial g_e}) + (i_{1q} i_{2q} \frac{\partial L_m}{\partial g_e} + i_{2d} i_{1d} \frac{\partial L_m}{\partial g_e}) \quad (8)$$

$$F_{nr} = (i_{2q}^2 \frac{\partial L_2}{\partial g_e} + i_{2d}^2 \frac{\partial L_2}{\partial g_e}) + (i_{1q} i_{2q} \frac{\partial L_m}{\partial g_e} + i_{2d} i_{1d} \frac{\partial L_m}{\partial g_e}) \quad (9)$$

where, the air gap leakage induction is L_{peri},

C. Thrust force

The moving velocity of the primary carrier is u_r, the instantaneous thrust force is F_e, and F_e is P_G / u_r. The velocity e.m.f term P_G is rewritten as following,

$$P_G = \frac{3\pi}{2\tau} u_r L_m (i_{1q} i_{2d} - i_{1d} i_{2q}) \quad (10)$$

Accordingly, the thrust force F_e of SLIM is rewritten as following,

$$F_e = \frac{3\pi}{2\tau} L_m (i_{1q} i_{2d} - i_{1d} i_{2q}) \quad (11)$$

where, the secondary flux leakage must be agreed on d-axis to control the q-axis with a thrust component as following,

$$\lambda_{2q} = 0, \qquad \lambda_{2d} = const. \quad (12)$$

The thrust force of SLIM from the Eq. (12) is given as following,

$$\lambda_{2d} = L_m i_{1d} \quad (13)$$

$$F_e = -\frac{3\pi}{2\tau} L_m i_{1d} i_{2q} \quad (14)$$

$$F_e = -\frac{3\pi}{2\tau} \lambda_{2d} i_{2q} \quad (15)$$

In order to control thrust force of SLIM directly, the prmary current i_{1q} is writtem as following,

$$i_{1q} = \frac{2\tau L_2}{3\pi \lambda_{2d} L_m} F_e \quad (16)$$

From equation (16), The reference V_{1q}^* is gotten from the i_{1q} which controlled by the PI controller, and it has gotten the control pattern for the direct thrust force control by the Space Vector modulation.

3. RESULTS

The SLIM used in this experiment has the specification as following. 58.5[cm] in width, 57[cm] in length, 8.5[cm] in height, 110[kg] in weight. The experimental results with it show a step response to the reference speed 2[m/sec].

A. Control system of SLIM

The block diagram for the direct thrust control of SLIM in conveyance system is shown by Fig. 3.

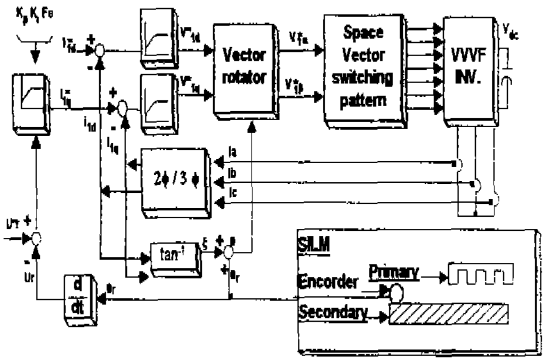


Fig. 3 The thrust control of SLIM in conveyance system

B. Thrust force and normal force

Fig. 4 shows the results of the thrust and the normal force by the direct thrust control system of SLIM. In the Fig. 4, the thrust waveform shows the stable result without the thrust ripple after .5[sec], which is converged to the nearest 0[N] and the normal force shows the stable result after .5[sec] also.

C. i_{1d}, i_{1q} and air gap

The waveform characteristics of the d-q axis current which inclued the thrust and the flux component show as Fig. 5. The thrust current i_{1q} as following the thrust reference i_{1q}^* tracks the reference and shows the stable result after .5[sec]. The flux current i_{1d} shows the stable result after .5[sec].

Also, Space Vector control restrained harmonic component for movement of a high efficiency and use of a voltage is used for the direct thrust control, and it is keeping up constantly a vibration of the air gap which caused of the thrust ripple.

D. Current and PWM

The PWM waveform has made by the Space Vector Modulation for the current control shown Fig. 6. When SLIM starts as shown from Fig. 6(a), the PWM waveform changes about during .7[sec] and after this, it is being stability. When SLIM brakes, the PWM waveform and the current show as Fig. 6(b).

F. Velocity and current

Fig. 7(a), (b) show the results of the velocity and the current characteristic, which show a step response to the reference velocity 2[m/sec]. It took about .5[sec] to reach the reference value and about .5[sec] to brake.

Fig. 7 shows a response without the thrust ripple by the Space Vector control. Therefore, we are able to control a direct thrust of SLIM based on these results.

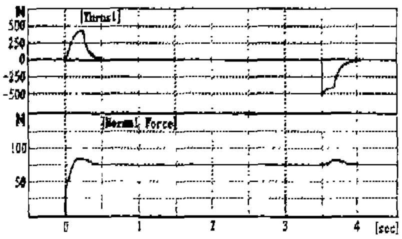


Fig. 4 Thrust force and normal force

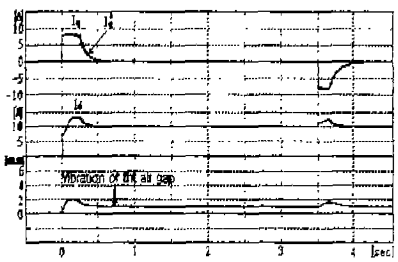
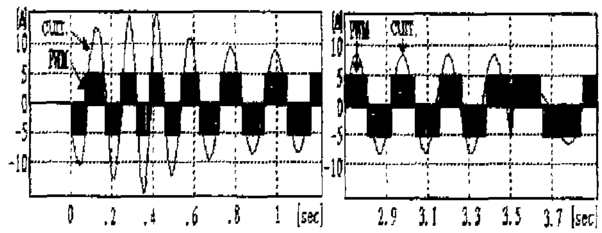
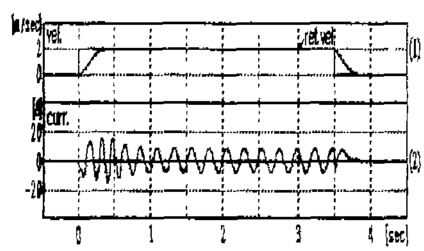


Fig. 5 i_d, i_q and air gap

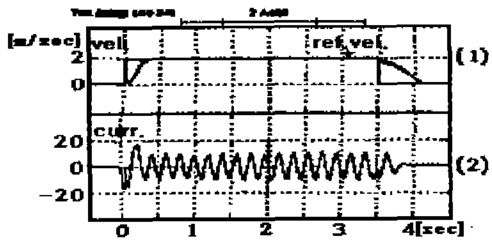


(a) (b)

Fig. 6 PWM waveform and current



(a)Simulation



(b)Experiment

Fig. 7 Current and velocity

4. CONCLUSIONS

In this paper, the direct thrust control of SLIM in conveyance system is proposed.

(1)The q axis equivalent circuit is obtained from the voltage equation by SLIM and we got the thrust component as a function of velocity, could the direct thrust control by PI controller.

(2)The thrust ripple due to the air gap vibration is reduced by the Space Vector control and the stable results are obtained.

These results offer the possibility of the direct drive and the precise position control of SLIM in conveyance system.

5. REFERENCES

[1]Jacek F. Gieras, "Linear Induction Drives", OXFORD SCIENCE PUBLICATIONS, 1994.

[2]T.A.Nondahl & D.W. Novotny, "Pole-by-Pole Model of a Linear Induction Machine Using Conformal Mapping Coefficients", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No.4, July/Aug, 1979.

[3]C.Lu, T.R.Eastham, G.E.Dawson,"Transient and Dynamic Performance of a Linear Induction Motor", IEEE Conf. IAS Annual Meeting, pp.266~273, 1993.

[4]J.S.Kim, S.K.Sul, "A Novel Voltage Modulation Technique of the Space Vector PWM," IPEC'95 Yokohama Conf, pp.742~747, 1995.