Control of a Linear Permanent Magnet Synchronous Motor using Multiple Reference Frame Theory

Jawad Faiz and B. Rezaei-Alam
Department of Electrical and Computer Engineering
Faculty of Engineering
University of Tehran, Tehran, Iran.
Email: faiz-j@sofe.ece.ut.ac.ir

Key words: **Feeding Current Minimization, Linear Motor, Multiple Reference Frame.**

Abstract: **This paper uses a multiple reference frame theory (MRF) in order to estimate and control the current harmonics of a linear synchronous motor with permanent magnet stator structure (PMLSM). This is done in such a way that the rms supply current is minimized, therefore the losses will be lower. Also relationship between the traction force and currents of the motor is studied in dq axes. The suggested technique is robust against time-variable parameters such as inductance variation. Finally simulation results of the suggested structure are presented.**

1 INTRODUCTION

Linear motors are convenient for rapid transport with no acoustic noise and high performance. The major advantage of using the linear motors is transferring the applied force on the moving object without a mechanical interface. Vector control technique is satisfactorily applied to rotating motors and there are also reports concerning the vector control application in linear motors [1]. Generally in such application it is assumed that the electrical quantities vary sinusoidally, while the end-effect and inductances variations are non-sinusoidal. Therefore dq model of linear motors in synchronous flux cannot be used. Meanwhile it is difficult to compensate the longitudinal end effect along the vehicle, while the flux produced by the primary current repeats periodically and it cannot compensate the flux reduction at the beginning of the linear motor.

These are the reasons that it is difficult to investigate the harmonics caused by the longitudinal end effect and non-sinusoidal inductances. Also there are higher losses in linear motors because of longitudinal and cross end effects, large leakage flux and saturation of the teeth.

In [2] multiple reference frame (MRF) theory has been suggested for estimation and control of the current harmonics in the brushless direct current motor (BLDCM) and good results have been obtained. This can reduce the ripples of the developed torque and improve the efficiency of the motor. This method does not require Fourier series coefficients of the current wave .

In [3] the MRF theory has been recommended for modeling a PMLSM with non-sinusoidal line-to-line inductances. Harmonics of the current is obtained using the series expansion and every harmonic transfers to the relevant synchronous reference frame and separate control is applied.

The present paper uses the model given in [3] and a control structure is suggested for a PMLSM with non-sinusoidal back-emf waveform. A minimum supply current is achieved by injecting proper current harmonics which reduces the losses. The recommended technique does not require Fourier series coefficients of the current waveform and it is robust against time-variable parameters such as inductance change under saturation. Finally the simulation results are presented for the proposed structure.

2 MODELING OF A PMLSM

Fig. 1 shows the proposed PMLSM with specifications given in Table 1. The system voltage equations of the motor circuit are as follows:

$$V_{abc}=R\, i_{abc}.+d/dt(\Lambda+\Lambda_m) \qquad 1$$

Where

$$R=diag[r\ r\ r] \quad i_{abc}=[i_a\ i_b,\ i_c]^T,\ V_{abc}=[V_a\ V_b\ V_c]^T$$

$$\Lambda_m=\lambda_m \sum_{n=1,3,5} k_{qn}[\sin(n\theta)\ \ \sin(n(\theta-\varphi))\ \ \sin(n(\theta+\varphi))]^T$$

$$\Lambda=LI\ ,\ L=[L_{11}\ \ L_{12}\ \ L_{13} \\ L_{21}\ \ L_{22}\ \ L_{23} \\ L_{31}\ \ L_{32}\ \ L_{33}]$$

$$L_{11}=L_N+L_B\cos(2(\theta-\varphi))+L_C\cos(4(\theta+\varphi))$$
$$L_{22}=L_N+L_B\cos(2\theta)+L_C\cos(4\theta)$$
$$L_{33}=L_N+L_B\cos(2(\theta+\varphi))+L_C\cos(4(\theta-\varphi))$$
$$L_{12}=L_{12}=L_v+L_B\cos(2(\theta+\varphi))+L_C\cos(4(\theta-\varphi))$$
$$L_{13}=L_{31}=L_v+L_B\cos(2\theta)+L_C\cos(4\theta)$$
$$L_{23}=L_{32}=L_v+L_B\cos(2(\theta-\varphi))+L_C\cos(4(\theta+\varphi))$$

$$\Theta=2\pi x/3,\quad \varphi=2\pi/3,\quad L_N=L_{ls}+L_A,\quad L_v=-L_A/2$$

TABLE 1. SPECIFICATIONS OF THE PROPOSED MOTOR

Quantity	Value
Number of phases	3
Number of poles, P	4
Winding resistance, R	2.75 Ω
Inductance, L_A	2.2 mH
Leakage inductance, L_l	0.2 mH
Positive sequence inductance, L_B	0.09 mH
Negative sequence inductance, L_C	0.05 mH
Mass, m	0.2 kg
Friction coefficient, B_v	0.1
1st Fourier coefficient, K_{q1}	1
3nd Fourier coefficient, K_{q3}	-0.121
5th Fourier coefficient, K_{q5}	-0.006
λ_m	0.053 Vs/rad

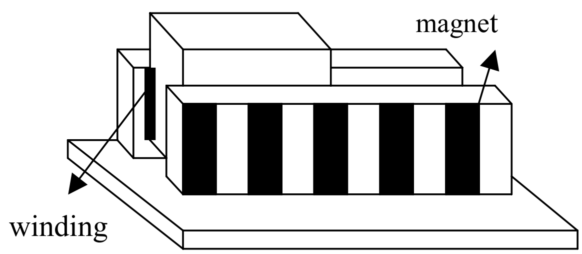

Fig. 1. Proposed linear PM LSM with a short primary

the electric force equation in a linear motor can be obtained as follows [4]:

$$F=0.5P\{-0.5(i_{abc})^T\partial/\partial x[L-L_lI]\ i_{abc}+(i_{abc})^T\partial/\partial x[\Lambda_m]\} \qquad 2$$

The mechanical equations are:

$$F=ma+B_vV_x+F_L=mdV_x/dt+B_vV_x+F_L \qquad 3$$

Now the Park's transformation can be applied and dependency of the inductances on the position is eliminated. By defining matrix K_n as follows:

$$K_n=\sqrt{2/3}\ [\ \cos(n(\theta-\pi/3))\ \ \cos(n(\theta-\pi))\ \ \cos(n(\theta+\pi/3)) \\ \sin(n(\theta-\pi/3))\ \ \sin(n(\theta-\pi))\ \ \sin(n(\theta+\pi/3)) \\ 1/\sqrt{2}\ \ 1/\sqrt{2}\ \ 1/\sqrt{2}\ ] \qquad 4$$

nth harmonic of the current can be transferred to the corresponding synchronous flux axes and obtain i_{dn} and i_{qn}. Assuming i_{dn}=0, force equation for any harmonic will be as follows:

$$F_n=(\pi/\tau)(\lambda_m K_{qn} i_{qn}) \qquad 5$$

And the total average force is:

$$F=\sum_n F_n \qquad 6$$

3 MINIMIZATION OF SUPPLY CURRENT

Now a current vector is obtained where its rms value is minimal over different modes of operation. Minimization of the rms current leads to the reduction of the inverter and primary winding losses. It is necessary to define two current and flux-linkage coefficients as follows:

$$I_q=[\, i_{q1} \;\; i_{q2} \ldots \; i_{qn}]$$
$$K=[\, K_{q1} \;\; K_{q2} \ldots \; K_{qn}] \qquad 7$$

Based on Eqns. 5-6, the following equation can be obtained:

$$F=(\,\pi/\tau)\lambda_m K I_q^T \qquad 8$$

The i_{rms} must be minimized and the optimal current vector can be obtained using the norm minimum solution [5,6] as follows:

$$I_{Mc}=K^T F/(\,\pi/\tau)KK^T \qquad 9$$

4 CONTROL STRUCTURE

The structure of the drive has been shown in Fig. 2. Components of current i_{Mc} is calculated using Eqn. 9 and considering the mean value of the force. In this section, Fundamental and harmonics components of the current are estimated using MRF theory and they are controlled in such a way that they lead to the desirable values [2].

The multiple reference frame estimator (MRFE) block has been represented in Fig. 3. In this block, the three-phase currents are sampled and components of i_{dq} are estimated. First, in each branch, i_{dqn} components of the relevant harmonic are determined by the Park's transformation and then i_{dqn} components converge the actual value by the help of a integral loop with high gain.

The MRFR block in Fig. 2 regulates components of i_{dqn} current in such that i_{dqn} follows i_{dqn}^*. This block has been shown in Fig. 4. The integral of the current errors in any reference frame are transferred to the three-axes frame. Their summation gives the desirable primary windings current i_{abc}^*. This is applied to the voltage source inverter (VSI) with current supply. Stability of the above-mentioned technique has been proved in [2].

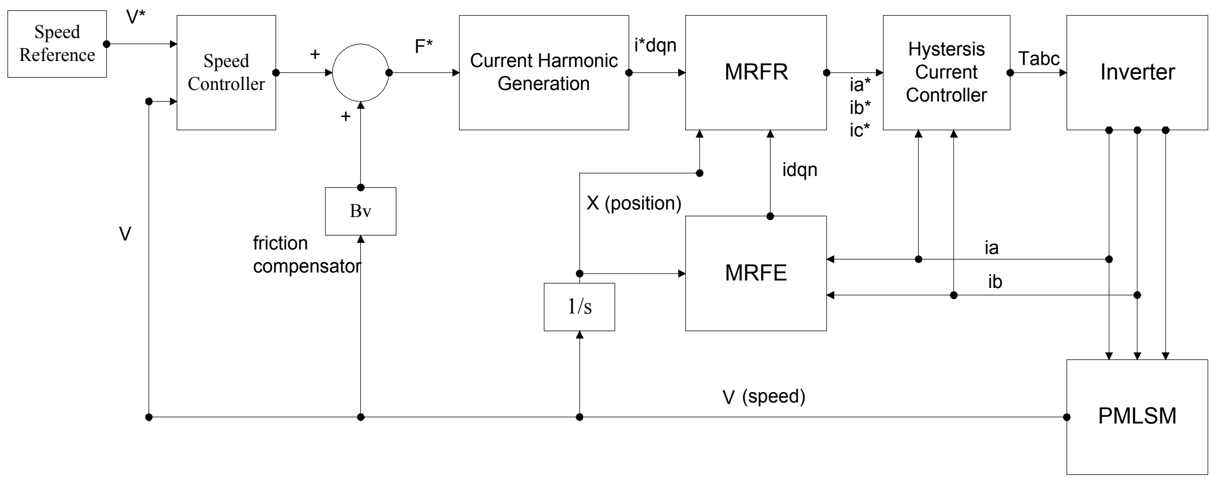

Fig. 2. Block diagram of the drive

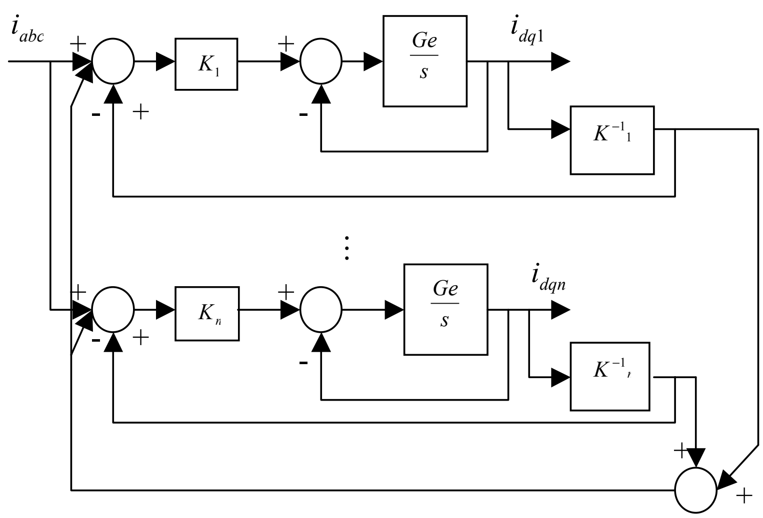

Fig. 3. Multiple reference frame estimator (MRFE)

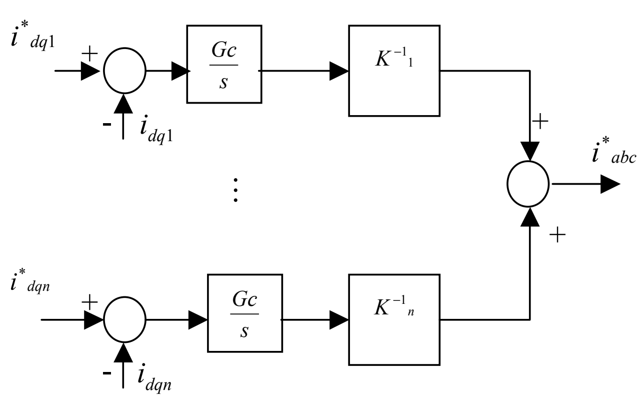

Fig. 4. Multiple reference frame regulator (MRFR)

5 SIMULATION RESULTS

The suggested algorithm has been applied to the proposed PMLSM. Taking into account the fundamental, 3rd and 5th harmonic simulation results have been obtained. It is noted that the technique can be applied to any number of harmonics. The flux waveform of the magnet with Fourier coefficients $K_{q1}=1$, $K_{q3}=-0.121$ and $K_{q5}=-0.006$ has been shown in Fig. 5. The step response of speed and the actual phase current i_a, converging the desirable i_a^*, have been presented in Fig. 6. The desirable value if i_{dn} is equal to zero, and as shown in Fig. 7, the actual value of i_{dn} approaches zero. i_{qn} has been converge its final value.

Fig. 8 indicates the influence of 30% reduction of inductance L_A due to saturation. When the Fourier series is used for the current harmonics this inductance change increases the torque ripples. However there is a slight torque ripples when MRF theory is used. Also this inductance reduction has no effect upon the supply current minimization, because the inductances have not been used in the control system.

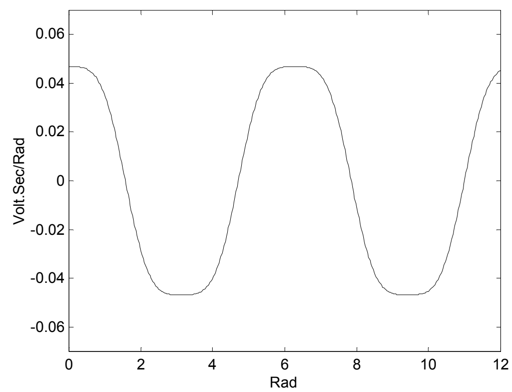

Fig. 5. Waveform of magnet flux

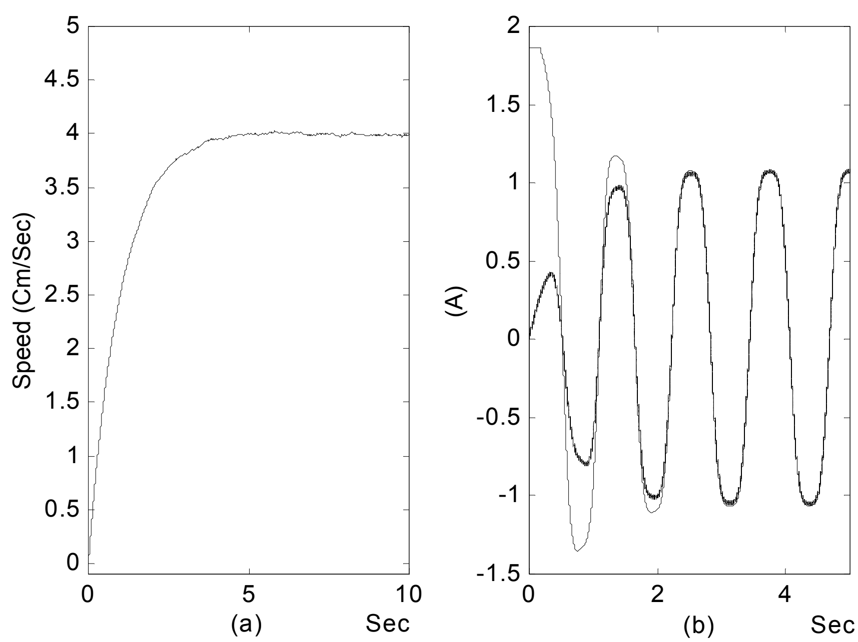

Fig. 6. Step response of the system speed

6 CONCLUSION

A control algorithm for a PMLSM has been recommended which can compensate the non-linear characteristics of the motor by injecting the convenient harmonics of current based on MRF theory. Therefore, some obstacleses in application of vector control in the linear motors are removed and the losses are considerably reduced by reduction of the rms current. The simulation results confirm the proper performance of the suggested technique.

7 References

1. Gu B. G. and Nam K., A vector control for a PMLSM considering a non-uniform flux distribution, IEEE APEC, 2000, pp. 393-396.

2. Chapman P. L. and Sudhoff S. D., A multiple reference frame synchronous estimator, IEEE Trans. On Energy Conversion, Vol.15, No. 2, pp. 197-202, 2000.

3. Liu C. T. and Hsu S. C., Analysis of linear electromagnetic motion devices by multiple-reference frame theory, IEEE Trans. on Magnetics, Vol. 34, No. 4, pp. 2063-2065, 1998.

4. Krause P. C., Analysis of electric machinery, McGraw-Hill, 1993.

5. Chapman P.L., Sudhaff S. D. and Whitcomb C. A., Optimal current control strategy for surface-mounted permanent-magnet synchronous machines drives, IEEE Trans. On Energy Conversion, Vol. 14, pp. 1043-1050, 1999.

6. Brogan W. L., Modern Control Theory, Prentice Hall, 1991.

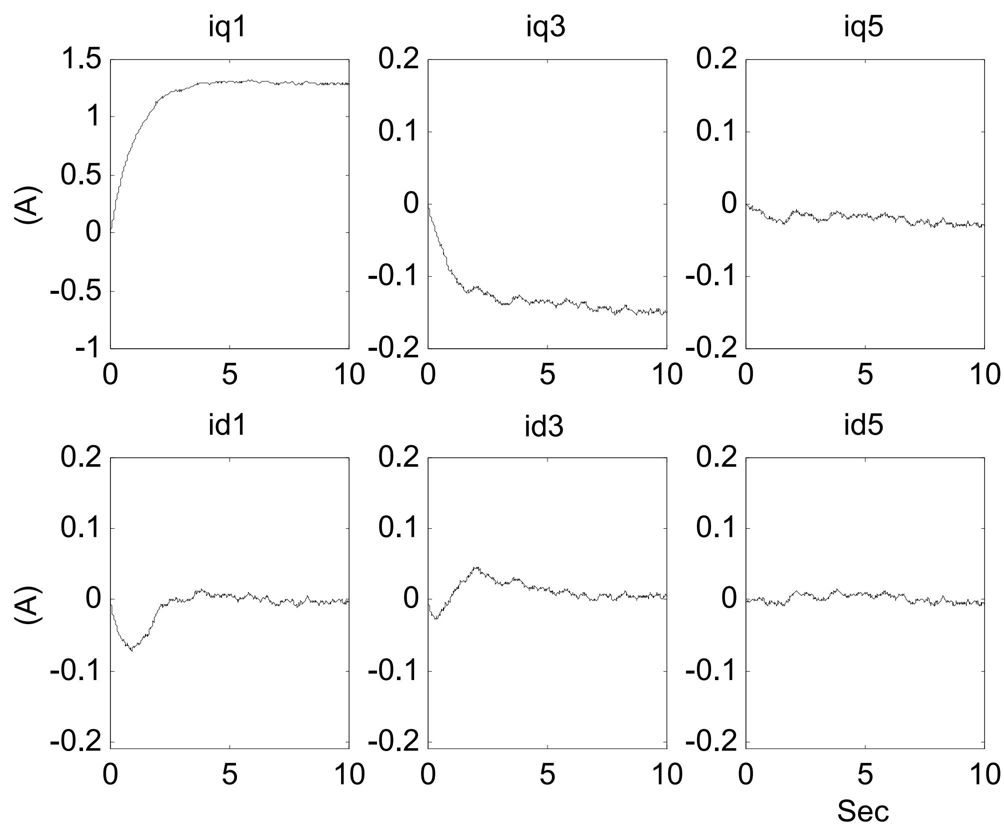

Fig. 7. Harmonic current response

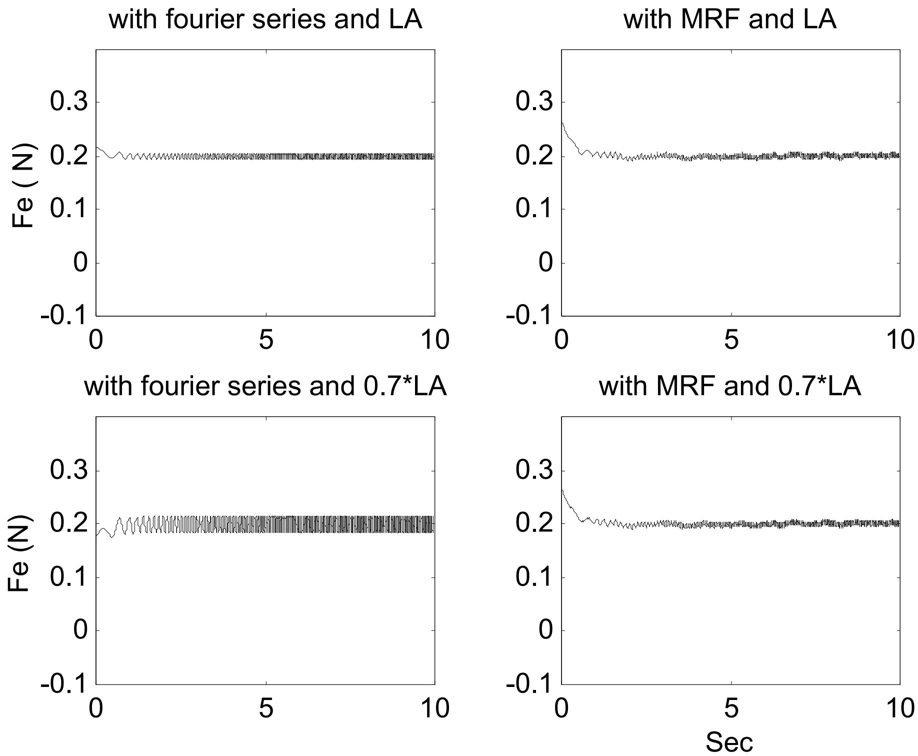

Fig. 8. Influence of 30% reduction of inductance L_A