SENSORLESS FIELD ORIENTATION CONTROL OF LINEAR INDUCTION MOTOR +

السيطرة على محرك حثي خطي بدون حساسات لتوجيه المجال

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Abstract:

Sensorless field oriented control of linear Induction Motor (LIM) as one types of vector control has permitted fast transient response by decoupled motor torque and flux control. The stator windings are described by coupled differential equations using mathematical transformations to decouple variables and refer all the variables to a common reference frame. The speed error is measured of applied load and according to error value, the set torque increases which requires increase in q current due to its direct relation with torque. In this paper, the velocity remains approximately constant during the interval of load application. The fluctuation of torque and motor current vanish, with increase in the stator current.

المستخلص:

تعتبر طريقة السيطرة على محرك حثي خطي بدون حساسات وبتوجيه المجال احد أشكال السيطرة الاتجاهية التي تمتاز بالاستجابة السريعة باستخدام عزم المحرك اللامرتبط وبتوجيه الفيض. تم تمثيل ملفات الثابت بمعادلات تفاضلية مرتبطة وباستخدام التحويل الرياضي ونسب كل الكميات الى مرجع عام. يتم قياس الخطأ في السرعة عند وضع حمل على المحرك وتبعا لقيمة الخطأ يتم زيادة العزم بواسطة مركبة التيار العمودية وذلك حسب العلاقة الرياضية بينهما. في هذا البحث تبقى السرعة تقريبا ثابتة خلال فترة الحمل، كما ان التذبذب في العزم والتيار ينتهي مع زيادة تيار العضو الثابت.

Introduction:

Various methods can be used to control the LIM torque and speed independently. These methods have varying complexity and performance depending on the method used. The main concept of these methods is by controlling of the voltage and frequency using switching power electronic devices known as inverters. The switching patterns of device are controlled through switching logic known as pulse width modulation (PWM). The main mode of control methods is scalar control and vector control method [1].

The scalar control can be used where the main controlling parameters are voltage V, current i, and magnetic flux linkage λ, which are defined by their magnitude and frequency, and those magnitude values observed and adjusted. This method is adopted in low-performance while for high performance operation, vector control is adopted in which the control variables consider the observation of values of stator voltage, current, and magnetic flux-linkage space vectors. Vector control is used to adjust the instantaneous values, from which, high dynamic perforce can be obtained [2].

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The concept of field orientation control is proposed for the first time to control the performance of rotary induction motor in a manner similar to the separately excited DC motor [2]. The main concept of sensorless field oriented control is similar to the direct field oriented control. The difference between direct and sensorless difference is that no feedback of propulsion force or rotor flux linkage are needed for the second one, and only speed rotor as feedback and to be subtracted from speed set point [3]. To satisfy this condition and ensuring field orientation, stator current d-component is obtained by given a desired level of rotor flux according to the flux equation. In this paper, sensorless field orientation control is adopted because the model under consideration is theoretical model and there is no experimental LIM that can be studied.

Analysis assumptions:

The following assumptions can be applied for simplification purposes [2]:
1- The primary winding is excited by sinusoidal current, which means only the fundamental wave is taken into account and harmonics current effects is not taken into consideration.
2- The iron saturation is neglected, which means that the magnetic conductance is independent of the current linkage. The magnetic voltage drop is negligible and in this case the solution is taken to be linear.
3- The neutral point of stare connection primary winding is not connected; therefore the voltage equations in rotor and stator will be reduced from three to two (zero voltages equations are neglected).
4- The slotting effects are neglected where current sheet is considered in order to simplify the equations solution.

Sensorless field orientation :

In this method the speed rotor error is used as feedback to be subtracting computed speed from speed set point [3]. To satisfy this condition and ensuring field orientation, stator current d-component is obtained by giving a desired level of rotor flux λ_r according to the flux equation. This method is adopted in the present work because it does not need to measure the air gap flux in d and q axes and rotor speed can be computed by using equation of motion, so that this method is suitable for theoretical control of linear induction motor (as there is no experimental model in the present work).

The electromagnetic torque T_{em} developed by the model is proportional to the product of the magnitude of space vector of the two motor variables, such as, current, flux linkage, or current and flux, and the sine of angle between these quantities.

In this method of control, dynamic transformation from stator reference frame dq to a revolving reference frame DQ are used [1]. This transformation is employed for the reason that under dynamic operating conditions, instantaneous speeds of the space vectors vary, and they are not necessarily the same for all vectors, the vectors keep revolving nevertheless. Consequently, their d and q components are AC variables, which are less convenient to analyze and utilize in a control system than the DC signals commonly used in control theory. The revolving reference frame is so selected that it moves in synchronism with a selected space vector. The DQ frame is rotating with frequency ω_e with the stator reference frame in the background. The stator current vector i_S revolves in the stator frame with angular velocity ω remaining stationary in the revolving frame if $\omega_e = \omega$. Consequently, the i_{DS} and

i_{QS} components in the latter frame are DC signals, constant in the steady state and varying in dynamic states. The transformation relation is given by [4]:

$$\begin{bmatrix} i_{DS} \\ i_{QS} \end{bmatrix} = \begin{bmatrix} \cos \omega_e t & \sin \omega_e t \\ -\sin \omega_e t & \cos \omega_e t \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \qquad (1)$$

Torque equation development:

The torque equation can be represented by the interaction of DQ components .The procedure used for the formulation of torque equation can be explained as follows:

- Primary instantaneous current transformed from ABC to dq using transformation equation:

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{SA} \\ i_{SB} \\ i_{SC} \end{bmatrix} \qquad (2)$$

Transformation from dq-component (stationary reference frame) to dynamic current component in DQ (revolving reference frame). For both stator supply voltage, flux linkage, rotor induced voltage and rotor flux linkage, the same relationship for current can be used. The current components can be treated as DC quantities when angular velocity is equal for both current vector and stator frame.

Reverse transformation from DQ to dq axis is given by [5]:

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} \cos \omega_e t & -\sin \omega_e t \\ \sin \omega_e t & \cos \omega_e t \end{bmatrix} \begin{bmatrix} i_{DS} \\ i_{QS} \end{bmatrix} \qquad (3)$$

The DQ-axis flux linkages of the stator given by [6]:

$$\begin{bmatrix} \lambda_{DS} \\ \lambda_{QS} \end{bmatrix} = \begin{bmatrix} L_s & L_m(1-f(Q)) & 0 & 0 \\ 0 & 0 & L_s & L_m(1-f(Q)) \end{bmatrix} \begin{bmatrix} i_{DS} \\ i_{DR} \\ i_{QS} \\ i_{QR} \end{bmatrix} \qquad (4)$$

Also, for DQ-axis flux linkages of the rotor given by:

$$\begin{bmatrix} \lambda_{DR} \\ \lambda_{QR} \end{bmatrix} = \begin{bmatrix} L_r & L_m(1-f(Q)) & 0 & 0 \\ 0 & 0 & L_r & L_m(1-f(Q)) \end{bmatrix} \begin{bmatrix} i_{DR} \\ i_{DS} \\ i_{QR} \\ i_{QS} \end{bmatrix} \qquad (5)$$

Torque equation is derived based on DQ axis [1]: $T_{em} = \frac{3p}{2} \frac{\pi}{\tau} L_m (1 - f(Q))(i_{QS} i_{DR} - i_{DS} i_{QR})$

Where: $i_{DR} = \frac{\lambda_{DR}}{L_r}$ and $i_{QR} = \frac{\lambda_{QR}}{L_r}$

Substituting i_{DR} and i_{QR} results in:

$$T_{em} = \frac{3p}{2}\frac{\pi}{\tau}\frac{L_m(1-f(Q))}{L_r}\left(i_{QS}\lambda_{DR} - i_{DS}\lambda_{QR}\right) \quad (6)$$

By aligning the D-axis of the revolving frame of reference with the rotor flux linkage vector, $\lambda_{QR} = 0$ [1]. The same result can be obtained by aligning the D-axis with another flux vector, which is stator or air gap flux vector, then equation (7 yields:

$$T_{em} = \frac{3p}{2}\frac{\pi}{\tau}\frac{L_m(1-f(Q))}{L_r}\left(i_{QS}\lambda_{DR} - 0\right)$$

Or

$$T_{em} = \frac{3p}{2}\frac{\pi}{\tau}\frac{L_m(1-f(Q))}{L_r} i_{QS}\lambda_{DR} \quad (7)$$

From equation (8), if the rotor flux linkage is not disturbed, the electromagnetic torque can be separately controlled by adjusting stator Q component i_{QS} .

Current and rotor angle computation:

As Q component of the rotor flux linkage $\lambda_{QR} = 0$, then equation 5 will be reduced to:

$$\lambda_{QR} = L_m(1-f(Q))i_{QS} + L_r i_{QR} = 0 \quad (8)$$

And

$$i_{QR} = -\frac{L_m(1-f(Q))}{L_r} i_{QS} \quad (9)$$

The voltage q-axis equation is given by [2]:

$$V_{QR} = R_r i_{dr} + p\lambda_{DR} + (\omega_e - \omega_r)\lambda_{DR} \quad (10)$$

If λ_{QR} remains unchanged, the derivative of λ_{QR} must be also zero and the result is:

$$0 = R_r i_{QR} + 0 + (\omega_e - \omega_r)\lambda_{DR}$$

$$\omega_{sl} = \omega_e - \omega_r = -\frac{R_r i_{QR}}{\lambda_{DR}} \quad (11)$$

Substituting i_{QR} from equation 10 results in:

$$\omega_{sl} = \frac{1}{T_r}\frac{L_m(1-f(Q))}{\lambda_{DR}} i_{QS} \quad (12)$$

Where $T_r = \frac{L_r}{R_r}$ is rotor time constant.

From equation 5 where λ_{DR} is:

$$\lambda_{DR} = L_r i_{DR} + L_m (1 - f(Q))(i_{DS}) \tag{13}$$

If λ_{DR} stay behind constant value then the its derivative will be also equal to zero $\frac{\partial \lambda_{DR}}{\partial t} = 0$, and by using the case of $\lambda_{QR} = 0$, i_{DR} must be zero and results in:

$$\lambda_{DR} = L_m (1 - f(Q)) i_{DS} \tag{14}$$

Also in similar way:

$$\omega_{st} = \omega_e - \omega_r = \frac{R_r}{L_r} \frac{i_{QS}}{i_{DS}} \tag{15}$$

The magnitude of secondary flux can be changed by controlling i_{DS} , this can be done by keeping either ω_{sl} or i_{QS} in appropriate field orientation. From equation 5:

$$i_{DR} = \frac{\lambda_{DR} - L_m (1 - f(Q)) i_{DS}}{L_r} \tag{16}$$

Substituting i_{DR} in rotor voltage equations:

$$V_{DR} = R_r i_{DR} + p\lambda_{DR} + (\omega_e - \omega_r)\lambda_{QR}$$

$$V_{QR} = R_r i_{QR} + p\lambda_{QR} - (\omega_e - \omega_r)\lambda_{DR}$$

Result

$$\lambda_{DR} = \frac{R_r L_m (1 - f(Q)) i_{DS}}{R_r + L_r p} \tag{17}$$

Decoupling between torque and rotor flux:

The angular position of rotor flux vector ρ is determined by adding the result of time integration of rotor frequency ω_{sl} (computed using equation 15) and angular displacement of the rotor θ_m [1, 6].

$$\rho = \int_0^t (\omega_e - \omega_r) dt + P\theta_m$$

$$\rho = \int_0^t \omega_{sl} dt + P\theta_m \tag{18}$$

Replacing $\omega_{sl}, \lambda_{DR}, i_{DS}, i_{QS}$ by

$\omega^*, \lambda_{DR}^*, i_{DS}^*, i_{QR}^*$ Yields:

$$\omega^* = \frac{L_m (1 - f(Q))}{T_r} \frac{i_{QS}^*}{\lambda_{DR}^*} \tag{19}$$

For steady state condition:

$$\lambda_{DR}^* = L_m (1 - f(Q)) i_{DS}^* \tag{20}$$

$$\omega^* = (\omega_e - \omega_r) = \frac{1}{T_r}\frac{i_{QS}^*}{i_{DS}^*} \tag{21}$$

From equation 17:

$$i_{DS}^* = \frac{1}{L_m(1-f(Q))}\left(T_r p \lambda_{DR}^* + \lambda_{DR}^*\right) \tag{22}$$

$$i_{QS}^* = \frac{2}{3p}\frac{\tau}{\pi}\frac{T_{em}^* L_r}{L_m(1-f(Q))\lambda_{DR}^*} \tag{23}$$

The transfer motion of the linear speed of the LIM rotor to an angular speed is to be used in model analysis equations which are given by [7]:

$$\omega_r = \frac{\pi}{\tau} V_r \tag{24}$$

The aim of indirect field orientation is to obtain decoupling between rotor flux linkages and torque. The equations used for transformation to synchronous reference frame are [2]:

$$i_{qs}^* = i_{QS}^* \cos\rho + i_{DS}^* \sin\rho \tag{25}$$

$$i_{ds}^* = -i_{QS}^* \sin\rho + i_{DS}^* \cos\rho \tag{26}$$

$$i_{SA}^* = i_{qs}^* \tag{27}$$

$$i_{SB}^* = -\frac{1}{2} i_{qs}^* - \frac{\sqrt{3}}{2} i_{ds}^* \tag{28}$$

$$i_{SC}^* = -\frac{1}{2} i_{qs}^* + \frac{\sqrt{3}}{2} i_{ds}^* \tag{29}$$

Sensorless field oriented simulink:

The sensorless field oriented control is designed by using the MATLAB 7.0/SIMULINK program, where mathematical blocks are used for LIM simulation using SIMULINK programming.

The procedures for LIM model simulation can be explained as follows:

1- The LIM model parameters is introduced as input data to the simulation program.

2- Set the reference speed ω_e^* in an array value of speed reference and the mechanical torque on the motor rotor T_{mech} also by an array value where the model is subjected to a sequence of step changes in load torque. Both for speed and torque, time arrays are used where the stop time is defined.

3- By making use of PI controller where its parameters are chose by trial and error. The input to the controller is the difference between the set reference speed and rotor computed speed and the output of the controller is T_{em}^* electromagnetic torque.

4- The rotor flux linkage λ_{DR}^* is defined by using look up table, [Appendix A]

5- Both of T_{em}^* and λ_{DR}^* are used as input to the field oriented control block. In this block i_{DS}^* and i_{QS}^* are computed using equations 22 and 23 respectively. The angular position of rotor ρ (the sum of slip angle and rotor angle) is determined using equation 21 for ω^* computation.

The predetermined values of i_{DS}^{*} and i_{QS}^{*} are used. The rotor angle θ_m is determined by taking the integration of computed rotor speed ω_r.

6-Transformation from DQ axis to dq axis is done using the reverse transformation relationship seen in equation 3.

7- Stator currents ($i_{SA}^{*}, i_{SB}^{*},$ and i_{SC}^{*}) are computed using equation 2.

8- The difference between the reference stator currents ($i_{SA}^{*}, i_{SB}^{*},$ and i_{SC}^{*}) and determined currents value ($i_{SA}, i_{SB},$ and i_{SC}) is computed. The current difference is used for computation of stator supply voltages.

9- The supply voltages are computed by multiplying the current difference with large shunt impedance for each phase. This impedance value depends on the base impedance. These voltages are computed in the ABC-axis.

10- The above voltages are transformed from ABC-axis to dq axis.

11- F_{em}, i_{ds}, i_{qs} Are computed, also rotor speed ω_r is determined.

12-Transformation of stator current i_{ds}, i_{qs} from dq axis to DQ axis, i_{SA}, i_{SB}, i_{SC} .

13- By making use of rotor speed, the end effects are introduced in the simulation, [Appendix B]. In this simulation, the model accelerates to speed using speed reference given by array at certain time while the rotor is subjected to step change of load also given by an array at certain time. The complete sensorless field control in block representation is shown in Appendix C, where this simulation contains all the basic principles of sensorless field orientation.

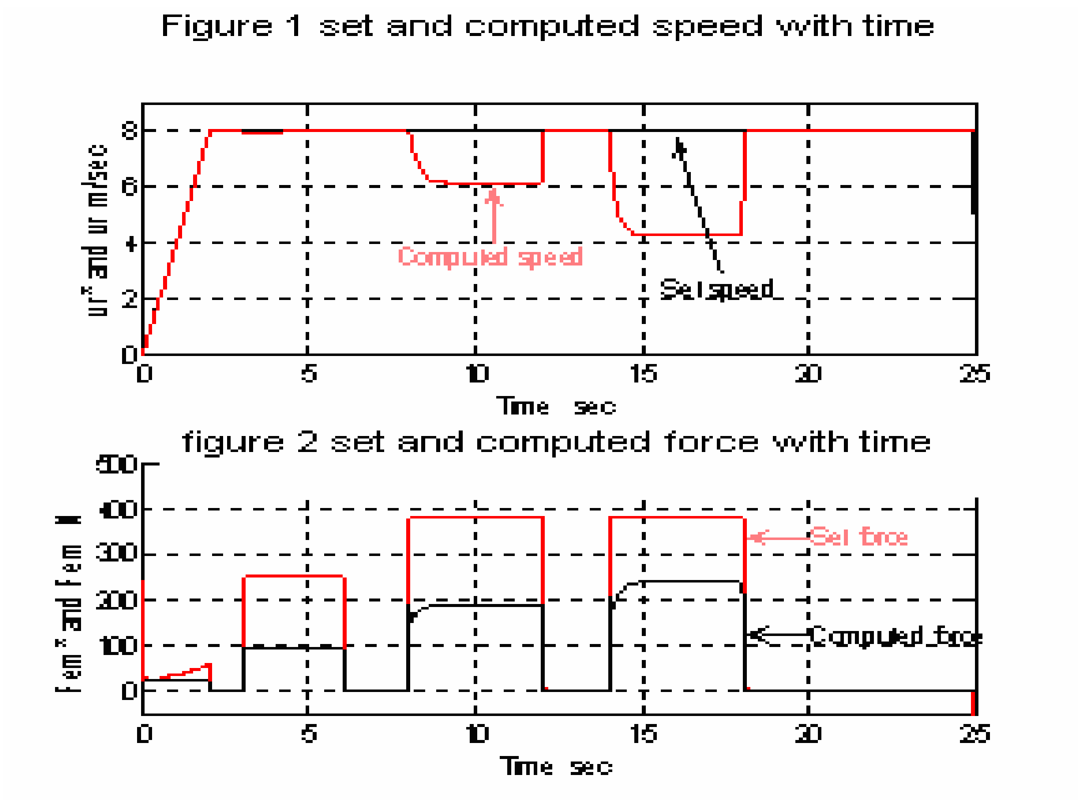
Results:

By using PI controllers as speed controller with array of time intervals (in second) of load application [0 3 3 6 6 8 8 12 12 14 14 18 18 25] and the array of load (in Newton) applied is [0 0 100 100 0 0 200 200 0 0 250 250 0 0] . The value of proportional gain (KP) is 25 , integral gain (KI) 10 , and force limit 400 N with sampling time 6E-3. The time array of set speed (in m/sec) repetition sequence is [0 2 25] and the value array of speed reference is [0 w_{set}* w_{set}*]

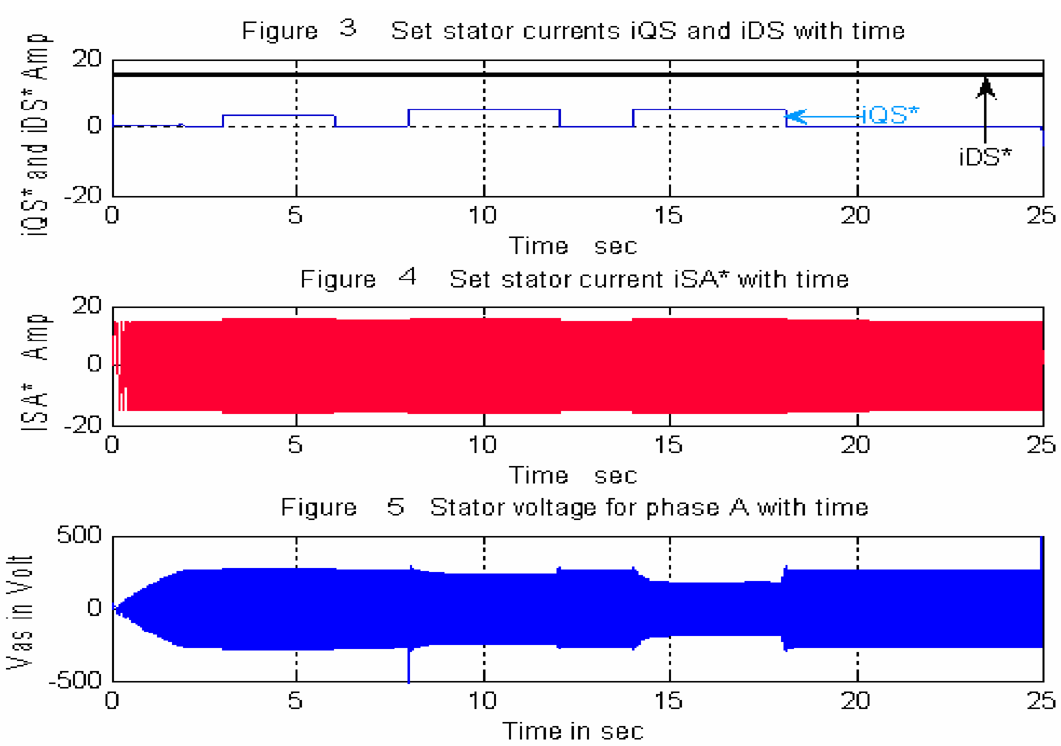
The speed simulation results are depicted in figure 1, where the set speed and computed speed are depicted in this figure. As shown, the speed reduces with the increase in applied load, and this reduction decreases with force limit in PI controller. The reduction of speed can be improved by increasing force limit in PI controller parameters. The speed ramps to rated speed for the first 2 seconds and the speed response is constant. At the time of load application, the speed is reduced and returns to its rated value with load removing. The fluctuation of speed depends on both proportional and integral gains of PI controller.

Set force depends on PI controller parameters and the main effective parameter is the force limit. With the force limit increasing, the set force increases also and electromagnetic force is equal to applied force demand as shown in figure 2. The oscillation at the instant of applying load can be modified by increasing force limit.

From field orientation formulation, which depends on the decoupling between torque and rotor flux linkage, the rotor force can be independently controlled by adjusting stator q component current. This can be depicted in figure 3, where the variation of i_{QS}^{*} according to the applied force and takes the value from 0 to 6 Amp. The current component i_{DS}^{*} is in direct relation with rotor flux linkage, which is assumed constant during control simulation, so that, the current remains constant.



The set stator current is depicted in figure 4, which varies with applied force. Stator voltage is computed depending on the difference between set stator current and computed stator current. This voltage is reduced with load applied and increasing at the time of removing load as shown in figure 5.



The variation of rotor flux linkage is less than that set value, which is computed from look up table as depicted in figure 6. When the load increases, rotor flux increases also. Stator voltage in q-axis changes according to the change in load applied as shown in figure 7. The stator current in d-axis is shown in figure 8, where the increase is clearly shown with increasing load.

Figure 6 Set and computed rotor flux linkage with time

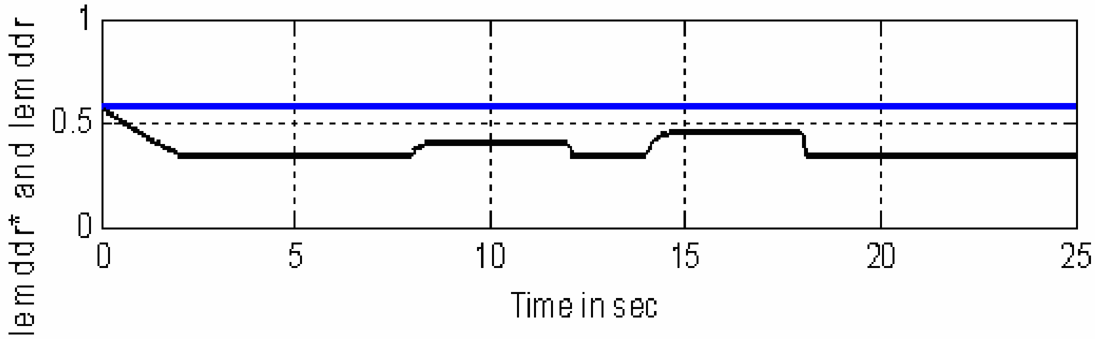


Figure 7 Stator voltage in q-axis with time

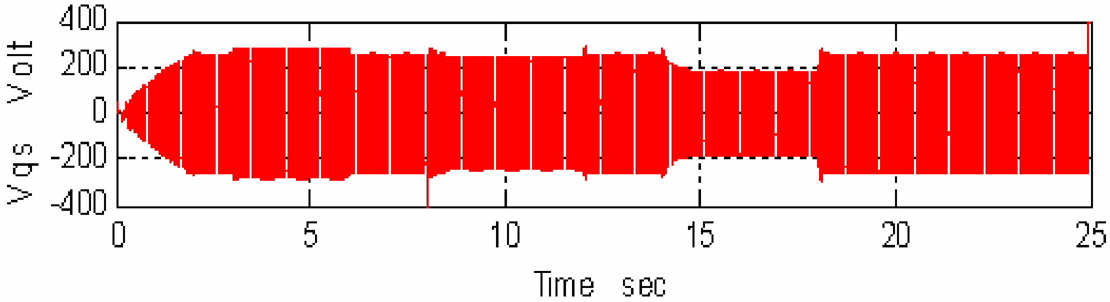
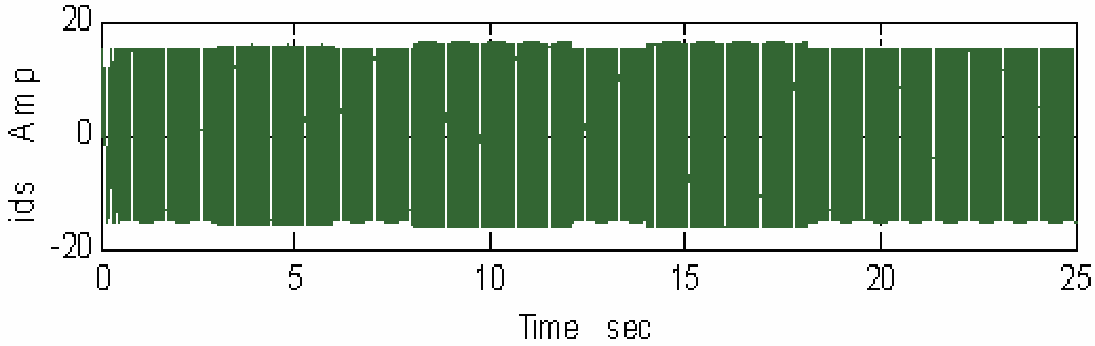
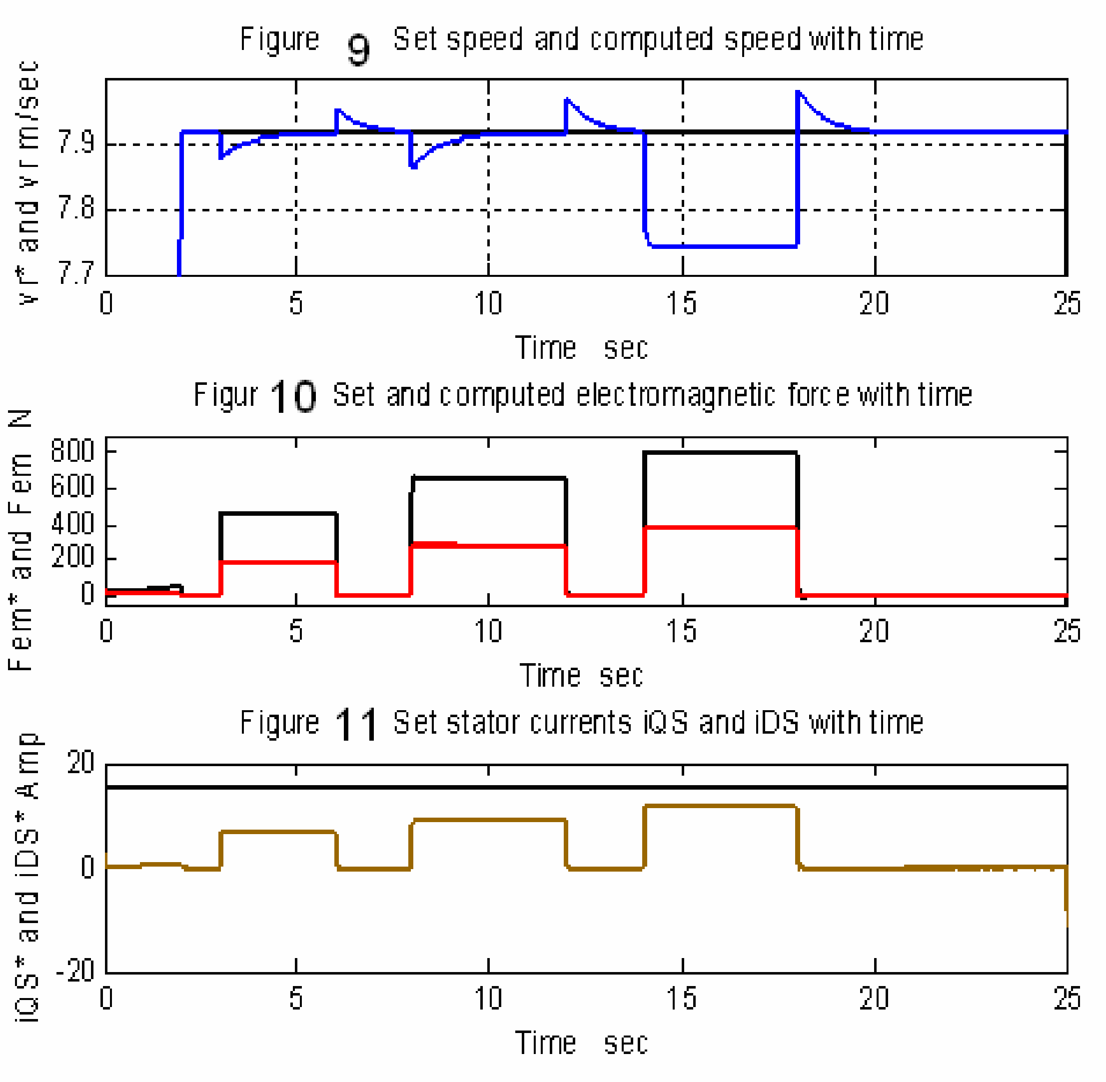


Figure 8 Stator current in d-axis with time



The increase of applied force to a certain array value [0 0 200 200 0 0 300 300 0 0 400 400 0 0] N needs to change PI controller parameters in order to fulfill the load requirement. The proportional gain is 10, integral gain 15, and the gain 17 where the integral gain is selected to be more than proportional gain in order to increase overshoot and to see later the effect of IP parameters. In figure 9, the overshoot at the instant of load application (3, 8, and 14, second) increases with increasing load. The settling time increases when load is increasing with the following values, 1.4, 1.6, and 1.8, computed from the instant of load removal.

The set force, obtained as output of PI controller, is shown in figure 10, where its magnitude increases with increasing applied load and the electromagnetic force fulfills load requirement. Also, Q component of field orientation current increases also as depicted in figure 11, while D component remains constant.



Conclusions:

For proper LIM operation to fulfill the essential load requirements such as rotor speed and torque, some sort of control must be used. By using vector control, the speed error (which represent the difference between set and computed speed) is measured which increases at the instant of applied load time. According to error value, the set torque increases which require increase in q current due to its direct relation with torque. The velocity remains approximately constant during the interval of load application. The resultant of speed constant is due to the using of direct field orientation control which found to be one of the effective methods of LIM control the can be used in different applications.

In this approach, the motor performance is controlled without using any sensor for measuring rotor speed or motor magnetic field and the feedback is ensure depending on computed speed and magnetic field.

Small fluctuation of torque and motor stator current at the instant of load applied and this fluctuation is vanish with increase in the stator current.

The change in rotor flux linkage in d axis shows the amount of flux response with load variation.

Effect of frequency supply increase is taken into account. This increase leads to increase of all motor reactance, which tends to increase terminal voltage in order to fulfill load requirement. In this approach, the motor performances is controlled without using any sensor for measuring rotor speed or motor magnetic field and the feedback is ensured depending on computed speed and magnetic field only, while most of the remaining control methods need actual measurement.

Appendix A:

Look up table details

The secondary linkage flux λ_{dr} value in the air gap is defined by using look up table which uses the secondary speed (computed from torque equation) to define λ_{dr} [2]. The table matches the desired value of λ_{dr} according to the speed value ω_m. When the speed is less than rated speed, then λ_{dr} is computed.

The rotor speed can be used to set the required rotor flux that will be induced in the air gap of the motor by using Look-Up Table block λ_{dr}. This table matches the desired value of the rotor d-axis flux with the rotor linear speed. When the speed of the rotor is less than the rated speed, the value of λ_{dr} is being equal to it's no load value at rated speed. The field weakening is shown in figure A.1.

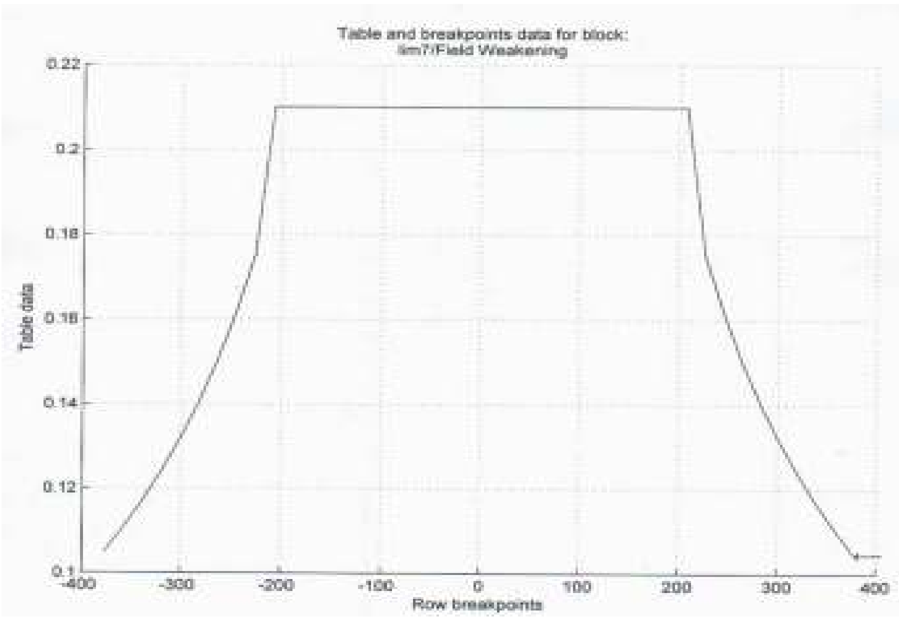


Figure A.1 field weakening of LIM [2]

Appendix B:

End effects formulation [8]

The main difference between rotary and linear machine is that the secondary in linear machine continuously replaced by a new material. This new material will tend to resist a sudden increase in flux penetration and only a gradual build up of flux density in the air gap. The entry of new material and its influence on the flux will modify the motor performance.

The spatial distribution of the flux density along the motor length will, however, depend on the primary speed relative to the secondary sheet. The distance moved by the primary in one secondary time constant is:

$$D = V_r T_r \qquad \text{(B.1)}$$

Where

$$T_r = \frac{L_m + L_{lr}}{R_r} \qquad \text{(B.2)}$$

For a given primary velocity, the distance can be expressed in terms of secondary time constant T_2 . The primary length on this normalized time scale obtained by computes the time taken for the motor to traverse a point on the long secondary as:

$$T_v = Dl V_r$$

The term T_v in terms of the T_r is:

$$Q = \frac{T_v}{T_r}$$

$$= \frac{DR_r}{(L_m + L_r)V_r} \qquad \text{(B.3)}$$

Q is dimensionless and represent motor length on this normalized time scale. According to this, the motor length is clearly depending on the motor velocity, so that; at zero velocity the motor length is infinitely long. When the velocity rises and the motor length will effectively shrink.

The value of secondary eddy current varies along the motor length. The average value of eddy current per unit length is:

$$i_{re} = \frac{i_m}{Q}\int_0^Q \exp(-x)dx$$

$$= i_m \frac{(1 - \exp(-Q))}{Q} \qquad \text{(B.4)}$$

The average value of magnetizing current per unit length is:

$$i_{me} = i_m - i_{re}$$

$$= i_m\left(1 - \frac{1 - \exp(-Q)}{Q}\right) \qquad \text{(B.5)}$$

The demagnetizing effect of the secondary eddy current can be represented by means of an inductance connected in parallel with the magnetizing inductance. The required value of the parallel inductance is:

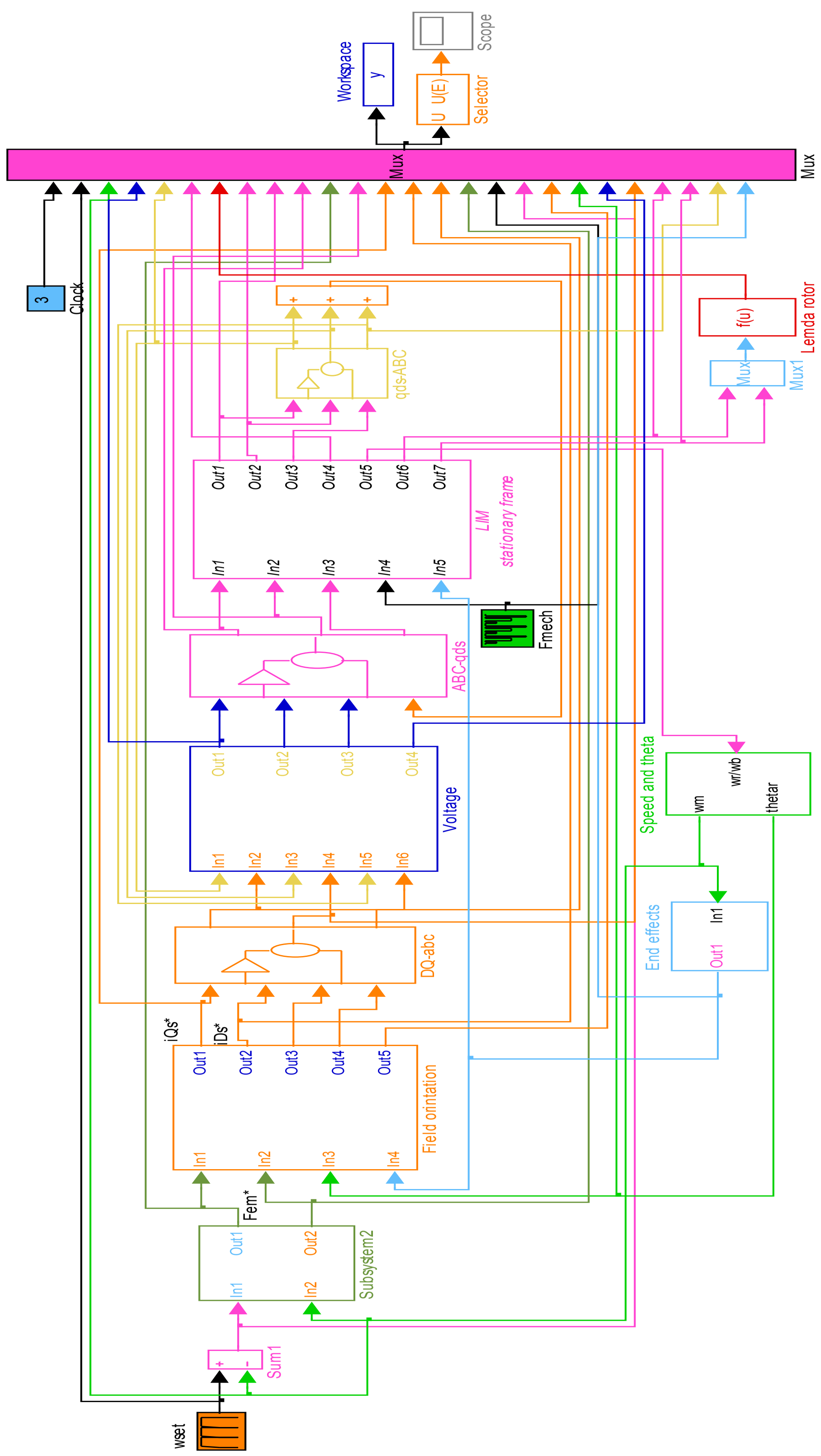
$$L_m = L_{m0}\frac{i_{me}}{i_{re}} = L_{m0}\left(\frac{Q}{1 - \exp(-Q)} - 1\right) \qquad \text{(B.6)}$$

This parallel circuit can be replaced by an equivalent inductance and this inductance obtained by:

$$L_m = L_{m0}\left(1 - \frac{1 - \exp(-Q)}{Q}\right) \qquad \text{(B.7)}$$

Appendix C:

Block diagram of LIM sensorless field orientation control scheme built in this work.



Symbols and definitions

i_{SA} Stator current, phase A

i_{SB} Stator current, phase B

i_{SC} Stator current, phase C

i_{DR} Rotor current in D-axis

i_{DS} Stator current in D-axis

i_{QR} Rotor current in Q-axis

i_{QS} Stator current in Q-axis

R_r Rotor resistance

T_{em} Electromagnetic torque

T_v Time to transfer point from primary to secondary

T_r Secondary time constant

V_r Rotor velocity

θ Angle

θ_r Angular position of rotor

λ_{DS} Stator flux linkage in D-axis

λ_{DR} Rotor flux linkage in D-axis

λ_{QR} Rotor flux linkage in Q-axis

λ_{QS} Stator flux linkage in Q-axis

λ_{ra} Rotor flux linkage of phase a

λ_{rb} Rotor flux linkage of phase b

λ_{rc} Rotor flux linkage of phase c

λ_{dr} Rotor flux linkage in d-axis

λ_{qr} Rotor flux linkage in q axis

λ_{SA} Stator flux linkage of phase A

λ_{SB} Stator flux linkage of phase B

λ_{SC} Stator flux linkage of phase C

ρ Angle between stator A-phase and rotor

τ Pole pitch

ω_r Angular speed

ω_e Angular speed of revolving frame

LIM data :

The linear induction motor model data that used in the present work are as shown in the present table:

Model part	Value	Unit
Air gap	0.0036	m
No. of pole	4	
No. of slot	29	
Slot/pole/phase	2	
Pole pitch	0.066	m
Coil pitch	5/6	
Turn/phase	240	
Turn/pole/phase	30	Double layer each layer 15 turn
Back iron depth	0.015	m
Rated voltage	220	Volt
Rated power	4400	Volt-Amp.
Stator self inductance	22.5E-03	Henry
Rotor self inductance	6.5E-03	Henry
Magnetization inductance	37.6E-03	Henry
Stator resistance	1.2	Ohm
Rotor resistance	2.7	Ohm

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