Modular Development of Linear Induction Motor Control in Simulink Environment

Bojidar Gueorguev Markov

Abstract –**In this paper, a modular Simulink implementation of a linear induction machine model is described in a step-by-step approach. With the modular system, each block solves one of the model equations; therefore, unlike black box models, all of the machine parameters are accessible for control and verification purposes. After the implementation, examples are given with the model used in different drive applications, such as open-loop constant V/Hz control.**

Keywords – **Linear induction motor, dynamic system, modular development, Simulink model.**

I. Introduction

The modern adjustable frequency AC electric drive, in particularly a linear induction drives, controlled by converter and programmable microcontroller. The advantage of linear drives is their works without gearbox and other transmission for transformation a rotation torque to linear force. The control of linear drives has small size and weight of the converter, ultimate protection, the ability to diagnose the state of the drive, the drive control of analog and digital signals, easy programming of work, ability to synchronize the joint work of the drives involved in the process and a number of other advantages are that opportunity for the mass deployment of frequency- adjustable asynchronous electric in practice. If not the straight requirements by the electrical drive in terms of range and accuracy of speed control it using simple schemes for scalar frequency regulation without speed feedback. These circuits operate on the principle U/f control with various ratios between of voltage and frequency. Creation of adequate models of frequency asynchronous electric drives, allow you to predict the behavior of the electric frequency. One possibility for modeling and management is driven by in Simulink environment. Simulink models of linear induction motors in are shown in [1-3], but these models are shown as "black boxes" without showing interconnections. Some of them [1-3] recommend using S-functions, which are software source codes for Simulink blocks. This technique does not fully utilize the power and ease of Simulink because S-function programming knowledge is required to access the model variables. S-functions run faster than discrete Simulink blocks, but Simulink models can be made to run faster using “accelerator” functions or producing stand-alone Simulink models. Both of these require additional expense and can be avoided if the simulation speed is not that critical. Another approach for traditionally induction motors is using the Simulink Power System [4] that can be purchased with Simulink. This blockset also makes use of S-functions and is not as easy to work with as the rest of the Simulink blocks. Reference [5] refers to an implementation approach similar to the one in this paper but fails to give any details. On the other side in this module doesn’t have linear motor. In this paper, a modular, easy to understand Simulink linear induction motor model is described. With the modular system, each block solves one of the model equations therefore, unlike black box models, all of the machine parameters are accessible for control and verification purposes. Simulink induction machine model discussed in this paper has been featured in a recent graduate level text book [5], and it also has been used in [4-5], and [4-5] in their research.

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II. Linear induction motor model

The linear induction machine d-q or dynamic equivalent circuit is shown in Fig. 1.

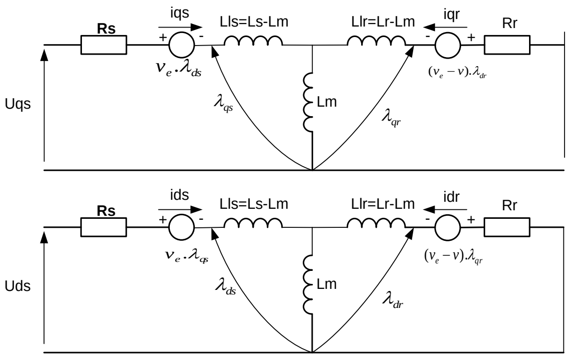

Fig.1. Dynamic model of linear induction motor

According to his model, the modeling equations in flux linkage form are as follows:

Equations should be centred and labelled. The example of equations is Eq. (1),

$$\frac{dF_{qs}}{dt} = v_b.[U_{qs} - \frac{v_e}{v_b}.F_{ds} + \frac{R_s}{x_{ls}}.(F_{mq} + F_{qs})] \qquad (1)$$

$$\frac{dF_{ds}}{dt} = v_b.[U_{ds} + \frac{v_e}{v_b}.F_{qs} + \frac{R_s}{x_{ls}}(F_{md} + F_{ds})] \qquad (2)$$

$$\frac{dF_{qr}}{dt} = v_b.\left[-\frac{(v_e - v)}{v_b}F_{dr} + \frac{R_r}{x_{lr}}.(F_{mq} - F_{qr})\right] \qquad (3)$$

$$\frac{dF_{qr}}{dt} = v_b.\left[\frac{(v_e - v)}{v_b}F_{qr} + \frac{R_r}{x_{lr}}.(F_{md} - F_{dr})\right] \qquad (4)$$

$$F_{mq} = x_{ml}^{*} \cdot \left[\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}} \right] \quad (5)$$

$$F_{md} = x_{ml}^{*} \cdot \left[\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}} \right] \quad (6)$$

$$i_{qs} = \frac{1}{x_{ls}} . \left(F_{qs} - F_{mq} \right) \quad (7)$$

$$i_{ds} = \frac{1}{x_{ls}} . \left(F_{ds} - F_{md} \right) \quad (8)$$

$$i_{qr} = \frac{1}{x_{lr}} . \left(F_{qr} - F_{mq} \right) \quad (9)$$

$$i_{dr} = \frac{1}{x_{lr}} . \left(F_{dr} - F_{md} \right) \quad (10)$$

$$F_e = \frac{3}{2} . \left(\frac{p}{2} \right) . \left(\frac{\pi}{\tau} \right) \frac{1}{v_b} . \left(F_{ds} . i_{qs} - F_{qs} . i_{ds} \right) \quad (11)$$

$$F_e - F_c = M . \left(\frac{2}{p} \right) \frac{dv}{dt} \quad (12)$$

where,
d, q - are axes of d,q coordinate reference frame;
s - primary variable;
r - secondary variable;
F_{ij} - the flux linkage (*i*=*q* or *d* and *j*=*s* or *r*);
U_{qs}, U_{ds} - *q* and *d*–axis primary voltages;
F_{mq}, F_{md} - *q* and *d* axis magnetizing flux linkages;
R_r, R_s - active secondary and primary resistances;
$x_{ls} = 2.f.\tau.L_{ls}$ - primary leakage reactance;
$x_{lr} = 2.f.\tau.L_{lr}$ - secondary leakage reactance;
$x_{ml}^{*} = 1 / \left(\frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}} \right)$;
i_{qs}, i_{ds} - *q* and *d*–axis primary currents; i_{qr}, i_{dr} - *q* and *d*–axis secondary currents;
M - mass of the linear induction motor;
p - number of poles;
τ - pole pitch;
F_e - linear force;
F_C - load force;
$v_e = 2.\tau.f$ -primary linear speed;
v_b - motor linear electrical base speed;
v - secondary linear speed.

The model of the linear induction motor can be represented by five differential equations shown above. To solve these equations, they must be presented in the form of state equation, i.e.: $\dot{x} = A.x + b$, where $x = [F_{qs}\ F_{ds}\ F_{qr}\ F_{dr}\ v]^T$ is a state vector. Note that $F_{ij} = \lambda_{ij} . \omega_b$ where F_{ij} is the flux linkage (*i*=*q* or *d* and *j*=*s* or *r*) and λ_{ij} is the flux.

In this case, state-space form can be achieved by inserting (5) and (6) in (1-4) and collecting the similar terms together so that each state derivative is a function of only other state variables and model inputs. Then, the modeling Eqs. (1-4) and (12) of a squirrel cage induction motor in state-space become:

$$\frac{dF_{qs}}{dt} = v_b \left[U_{qs} - \frac{v_e}{v} . F_{ds} + \frac{R_s}{x_{ls}} . \left(\frac{x_{ml}^{*}}{x_{lr}} . F_{qr} + \left(\frac{x_{ml}^{*}}{x_{ls}} - 1 \right) . F_{qs} \right) \right] \quad (13)$$

$$\frac{dF_{ds}}{dt} = v_b \left[U_{ds} - \frac{v_e}{v} . F_{qs} + \frac{R_s}{x_{ls}} . \left(\frac{x_{ml}^{*}}{x_{lr}} . F_{dr} + \left(\frac{x_{ml}^{*}}{x_{ls}} - 1 \right) . F_{ds} \right) \right] \quad (14)$$

$$\frac{dF_{qr}}{dt} = v_b \left[- \frac{(v_e - v)}{v_b} . F_{ds} + \frac{R_s}{x_{lr}} . \left(\frac{x_{ml}^{*}}{x_{lr}} . F_{qs} + \left(\frac{x_{ml}^{*}}{x_{lr}} - 1 \right) . F_{qr} \right) \right] \quad (15)$$

$$\frac{dF_{dr}}{dt} = v_b \left[\frac{(v_e - v)}{v_b} . F_{qr} + \frac{R_r}{x_{lr}} . \left(\frac{x_{ml}^{*}}{x_{ls}} . F_{qr} + \left(\frac{x_{ml}^{*}}{x_{lr}} - 1 \right) . F_{dr} \right) \right] \quad (16)$$

$$\frac{dv}{dt} = \left(\frac{p}{2.M} \right) . \left(F_e \text{-} F_C \right) \quad (17)$$

III. Simulink implementation of model of induction motor

The inputs of a linear induction machine are the three-phase voltages, their fundamental frequency, and the load torque. The outputs, on the other hand, are the three-phase currents, and the secondary linear speed. The d-q model requires that all the three-phase variables have to be transformed to the two-phase synchronously rotating frame. Consequently, the linear induction machine model will have blocks transforming the three-phase voltages to the d-q frame and the d-q currents back to three-phase. The linear induction machine model implemented in this paper is shown in Fig. 2. It consists of five major blocks: the o-n conversion, abc-syn conversion, syn-abc conversion, unit vector calculation, and the induction machine d-q model blocks.

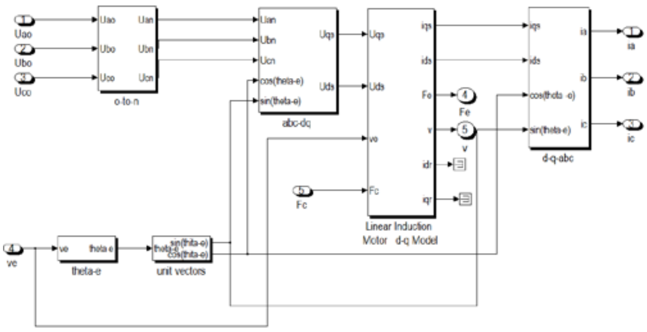

Fig. 2. The completed induction machine Simulink model

A. o-n block

This block is used for an isolated neutral system, otherwise it can be bypassed. The transformation done by this block can be represented as follows:

$$\begin{bmatrix} U_{an} \\ U_{bn} \\ U_{cn} \end{bmatrix} = \frac{1}{3} . \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \begin{bmatrix} U_{a0} \\ U_{b0} \\ U_{c0} \end{bmatrix} \tag{18}$$

This is implemented in Simulink by passing the input voltages through a Simulink "Matrix Gain" block, which contains the above transformation matrix.

B. Unit vector calculation block

Unit vectors $\cos\theta_e e$ and $\sin\theta_e$ are used in vector rotation blocks, "abc-syn conversion block" and "syn-abc conversion block". The angle θ_e is calculated directly by integrating the frequency of the input three-phase voltages:

$$\theta_e = \int \omega_e dt , \tag{19}$$

where $\omega_e = (\pi / \tau).v$

The unit vectors are obtained simply by taking the sine and cosine of θ_e . This block is also where the initial rotor position can be inserted, if needed, by adding an initial condition to the Simulink "Integrator" block. Note that the result of the integration in (19) is reset to zero each time it reaches $2.\pi$ radians so that the angle always varies between 0 and $2.\pi$.

C. abc-syn conversion block

To convert three-phase voltages to voltages in the two-phase synchronously rotating frame, they are first converted to two-phase stationary frame using (20) and then from the stationary frame to the synchronously rotating frame using (21).

$$\begin{bmatrix} U_{qs}^s \\ U_{ds}^s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} . \begin{bmatrix} U_{an} \\ U_{bn} \\ U_{cn} \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} U_{qs} \\ U_{ds} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} . \begin{bmatrix} U_{qs}^s \\ U_{ds}^s \end{bmatrix} \tag{21}$$

where the superscript "s" refers to stationary frame. Eq. (20) is implemented similar to (18) because it is a simple matrix transformation. Eq. (21), however, contains the unit vectors; therefore, a simple matrix transformation cannot be used. Instead, U_{ds} and U_{qs} are calculated using basic Simulink "Sum" and "Product" blocks.

D. syn-abc conversion block

This block does the opposite of the abc-syn conversion block for the current variables using (22) and (23) following the same implementation techniques as a point C:

$$\begin{bmatrix} i_{qs}^s \\ i_{ds}^s \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} . \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} \tag{22}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} . \begin{bmatrix} i_{qs}^s \\ i_{ds}^s \end{bmatrix} \tag{23}$$

E. Linear induction machine d-q model block

Fig. 3 shows the inside of this block where each equation from the induction machine model is implemented in a different block. First consider the flux linkage state equations because flux linkages are required to calculate all the other variables. These equations could be implemented using Simulink "State-space" block, but to have access to each point of the model, implementation using discrete blocks is preferred. Fig. 4 shows what is inside of the block solving (1). All the other blocks in Column 1 are similar to this block.

Once the flux linkages are calculated, the rest of the equations can be implemented without any difficulty. The blocks solving the rest of the equations are also organized in columns. The blocks in Column 2 solve (5) and (6). Eqs. (7-10) use the flux linkages to solve for the stator and rotor *d* and *q* currents. The fourth and the last column includes the electrical force calculation from (11) and the secondary element linear speed calculation using the last state Eq. (12); the implementation of which is shown in Fig. 5. The rotor speed information is required for the calculation of the secondary element flux linkages in Column 1; therefore, it is fed back to two blocks in this column. The resulting model is modular and easy to follow. Any variable can be easily traced using the Simulink 'Scope' blocks. The blocks in the first two columns calculate the flux linkages, which can be used in vector control systems in a flux loop. The blocks in Column 3 calculate all the current variables, which can be used in the current loops of any current control system and to calculate the three-phase currents. The two blocks of Column 4, on the other hand, calculate the torque and the speed of the linear induction machine, which again can be used in force control or speed control loops. These two variables can also be used to calculate the output power of the machine.

operation. Any machine control algorithm can be simulated in the Simulink environment with this model without actually using estimators. If need be, when the estimators are developed, they can be verified using the signals in the machine model.

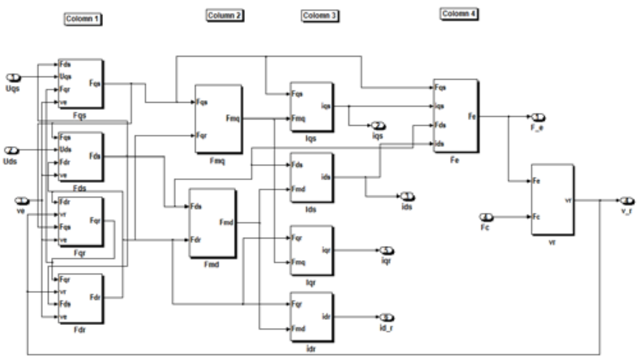

Fig. 3. Linear induction motor dynamic model in Simulink

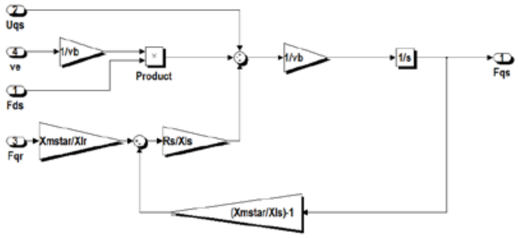

Fig. 4. Implementation one of module in column (1)

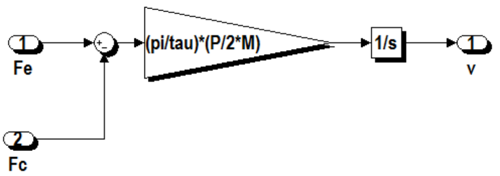

Fig. 5. Implementation of (12) in Simulink

IV. Simulation Results

Fig. 6 shows the implementation of open-loop constant V/Hz control of a linear induction machine. This figure has two new blocks: command voltage generator and 3-phase PWM inverter blocks. The first one generates the three-phase voltage commands, and it is nothing more than a “syn-abc” block explained earlier. The latter first compares the reference voltage, v_{ref} to the command voltages to generate PWM signals for each phase, then uses these signals to drive three Simulink “Switch” blocks switching between $+V_d/2$ and $-V_d/2$ (V_d is dc link voltage). The open-loop constant V/Hz operation is simulated for 1.2s ramping up and down the speed command and applying step load torques. The results are plotted in Fig. 7 where the response of the drive to changes in the speed command and load disturbances can be observed.

V. Conclusion

In this paper, implementation of a modular Simulink model for linear induction machine simulation has been introduced. Unlike most other linear induction machine model implementations, with this model, the user has access to all the internal variables for getting an insight into the machine operation.

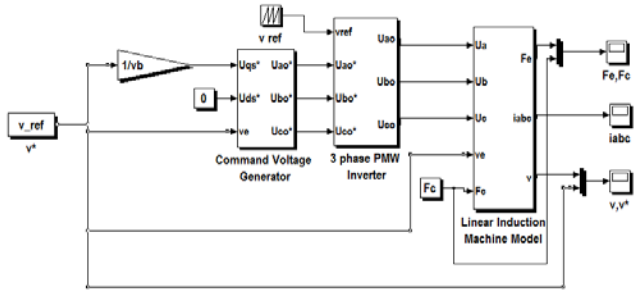

Fig. 6. Open loop constant V/Hz control Simulink model

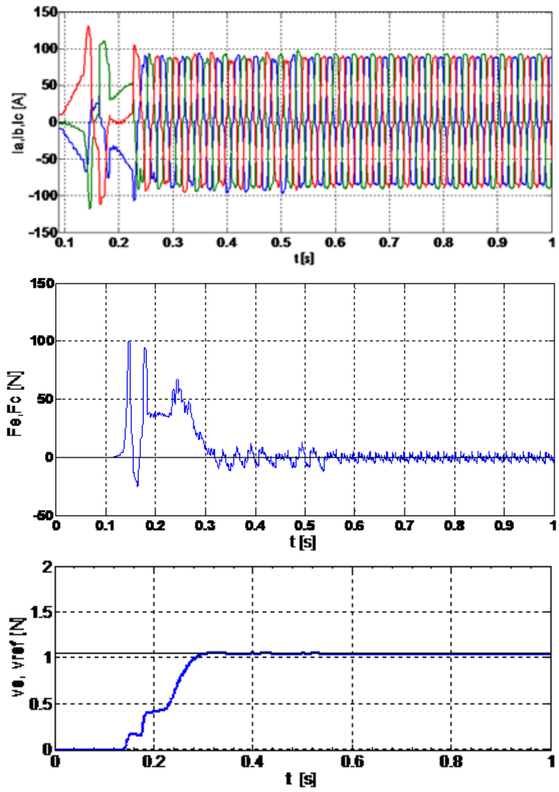

Fig. 7. Simulation results open loop constant V/Hz control

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