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Research Article

A Novel Comparison Study of Modelling Linear Induction Motor using Two Different Dynamic Approaches with Considering the End Effects

Fatimah F.Jaber*, Diyah K. Shary and Haider Alrudainy

Electrical Power Techniques Engineering Department, Southern Technical University, Basra, Iraq

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Abstract

Owing to its merits like lower costs, high starting thrust force, easy maintenance, less mechanical losses, silence, high precision, and so on Linear Induction Motor (LIM) is being increasingly utilized in industries. In this paper, a comparison between two different mathematical models of a LIM based upon the d-q axes equivalent electrical circuit has been investigated. This has been accomplished to define the dynamic performance of LIM when considering the end effects, which can be directly applicable for vector control and drive implementations. The first model separates the primary and secondary(linor) d-q axis currents into two components, one part is free from end effects while the other is based on end effects. The second model, however, takes currents without separating them. In the present study, the linear induction motor responses such as velocity developed thrust, and currents have been simulated and outputted using the MATLAB/SIMULINK toolbox. The simulation results showed that the approach with separating currents is superior than the second model in terms of velocity and thrust force by approximately of an 8.5% and 2.6% respectively.

Keywords: *Linear Induction Motor (LIM), end effects, Conventional induction motor (IM), modeling, and simulation.*

1. Introduction

Due to specific properties that LIMs drive possess, they are widely adopted in industrial applications, particularly in transportation. However, Driving a precise model of a LIM that can be used directly in vector control implementations is a challenging task for researchers. Therefore, many exploratory research under way investigating how to propose an accurate and applicable model for these motors. Using the equivalent circuit is the easiest way to examine a LIM. Modeling of LIM using an equivalent circuit, however, is not easier than in a conventional induction motor owing to the presence of end effects(Pegah Hamedani and Abbas Shoulaie, 2013). A new flux is continually created at the moment when the primary moves at the entry side of the primary, while the exit side flux will disappear. There is a fast generation and the absence of the magnetic lines in the secondary layer creates statically induced currents. The flux of the air gap is influenced by the Eddy currents. As the speed rises the flux-profile and losses become severe this is named End-Effect in linear induction motor (M. Naga Raju and M. Sandhya Rani, 2018). In this work, the dynamic model of LIM is investigated in two different approaches, and the results have been compared.

*Corresponding author's ORCID ID: 0000-0003-1610-3971
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Using the first method thereby separating the d-q axis primary and secondary currents into two components. The first part is dependent on the end effects while the other part does not depend on it. Whereas, the second Approach of modeling the LIM uses the currents without separating them. The different reference frames can be used to simulate the dynamic model of LIM, such as an arbitrary reference frame, stationary reference frame, rotor reference frame, and synchronous reference frame (Merlin Mary N.J., et all, 2016).

In this study, the two dynamics models of the linear induction motor have been simulated using a synchronous reference frame (d-q axis rotate at a synchronous frequency).

Nomenclature

V_{ds}, V_{qs} d-q axis primary voltages (volts)
V_{dr}, V_{qr} d-q axis secondary voltages (volts)
i_{ds}, i_{qs} d-q axis primary currents (A)
i_{dr}, i_{qr} d-q axis secondary currents (A)
$\lambda_{ds}, \lambda_{qs}$ flux linkage of the primary in the d-q axis
$\lambda_{dr}, \lambda_{qr}$ flux linkage of the secondary in the d-q axis
R_s, R_r primary and secondary resistances (Ω)
L_s, L_l leakage inductances of primary and secondary (H)
L_m Mutual inductance (H)
P Poles Number

τ pole pitch (m)
D primary length (m)
Q factor linked to the length of primary
V velocity (m/sec)
ω_e angler velocity of the primary (rad/sec)
ω_r angler velocity of the secondary (rad/sec)
ω_{sl} slip frequency (rad/sec)
B viscous friction (kg/sec)

2. Mathematical Modeling of Lim with End Effects

In traditional induction motors, the end effects are not exactly obvious. In contrast, these effects became progressively relevant in LIM as the velocity of the motor increases. Thus, will be investigated end effects as a function of linear induction motor velocity(A. Boucheta, et all, 2009)(Hamed Hamzehbahmani, 2011).

2.1 D-Q Axis equivalent circuit of linear induction motor

A d-q axis equivalent circuit for LIM is exhibited in figure (1) and figure (2) respectively (Jianqiang Liu, et all, 2007) (Hajj Mansour, et all, 2013):

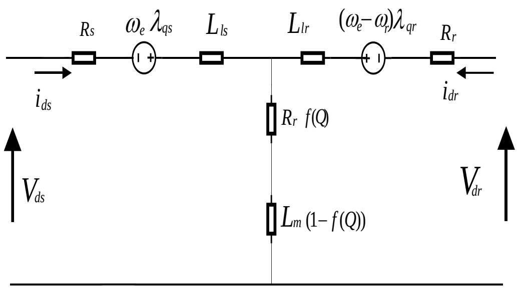

Fig.1 D-Axis equivalent circuit

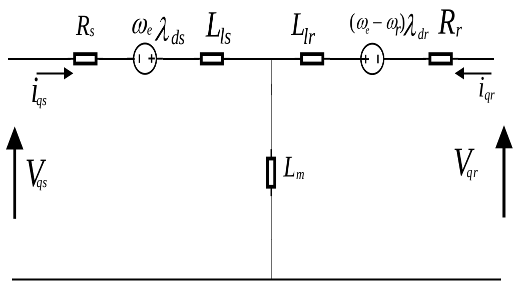

Fig.2 Q-Axis equivalent circuit.

2.2 Linear induction motor modeling without separating the currents

Depend on the d-q axis equivalent circuit of LIM, voltage equations of primary and secondary can be described in differential equations in the synchronous reference frame as (S. Vaez-Zadeh and M. R. Satvati, 2005) (Ameer L. Saleh, et all, 2018):

$$V_{ds} = R_s i_{ds} + R_r f(Q)(i_{ds} + i_{dr}) + p\lambda_{ds} - \omega_e\lambda\_qs \quad (1)$$

$$V_{qs} = R_s i_{qs} + p\lambda_{qs} + \omega_e\lambda_{ds} \quad (2)$$

$$V_{dr} = R_r i_{dr} + R_r f(Q)(i_{ds} + i_{dr}) + p\lambda_{dr} - \omega_{sl}\lambda_{qr} \quad (3)$$

$$V_{qr} = R_r i_{qr} + p\lambda_{qr} + \omega_{sl}\lambda_{dr} \quad (4)$$

$f(Q)$ is indicated as:

$$f(Q) = \frac{1 - e^{-Q}}{Q} \quad (5)$$

$$Q = \frac{D * R_r}{L_r\ v} \quad (6)$$

The flux linkages of primary and linor can be described / as:

$$\lambda_{ds} = L_{ls} i_{ds} + L_m\big(1 - f(Q)\big)(i_{ds} + i_{dr}) \quad (7)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m\big(i_{qs} + i_{qr}\big) \quad (8)$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m\big(1 - f(Q)\big)(i_{ds} + i_{dr}) \quad (9)$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m\big(i_{qs} + i_{qr}\big) \quad (10)$$

Thrust Force:

$$Fe = \frac{3\pi P}{2\tau_p\ 2}\big(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\big) \quad (11)$$

The primary and linor d-q currents in a linear induction motor are derivative from (7) to (10), Thus detaching i_{ds} from (7) and i_{dr} from (9) gives:

$$i_{ds} = \frac{\lambda_{ds} - L'_m i_{dr}}{L_{lr} + L'_m} \quad (12)$$

$$i_{dr} = \frac{\lambda_{dr} - L'_m i_{ds}}{L_{lr} + L'_m} \quad (13)$$

Detaching i_{qs} from(8) and $i_{qr}$from (10), we have:

$$i_{qs} = \frac{\lambda_{qs} - L_m i_{qr}}{L_S} \quad (14)$$

$$i_{qr} = \frac{\lambda_{qr} - L_m i_{qs}}{L_r} \quad (15)$$

Substitution of (13) in (12) and (12) in (13) gives:

$$i_{ds} = \frac{\big(L_r - L_m f(Q)\big)\lambda_{ds} - L_m\big(1 - f(Q)\big)\lambda_{dr}}{L_\sigma - L_m L_l f(Q)} \quad (16)$$

$$i_{dr} = \frac{\big(L_s - L_m f(Q)\big)\lambda_{dr} - L_m\big(1 - f(Q)\big)\lambda_{ds}}{L_\sigma - L_m L_l f(Q)} \quad (17)$$

Substituting (14) in (15) and (15) in (14) gives :

$$i_{qs} = \frac{L_r\lambda_{qs} - L_m\lambda_{qr}}{L_\sigma} \quad (18)$$

$$i_{qr} = \frac{L_s\lambda_{qr} - L_m\lambda_{qs}}{L_\sigma} \quad (19)$$

Where:

$$L_\sigma = L_s L_r - L_m^2 \quad (20)$$

$$L_l = L_{ls} + L_{lr} \quad (21)$$

The above equations were built in Matlab /Simulink environment to obtain the dynamic model of linear induction motor.

2.3 Linear induction motor modeling via separating the d-q axis primary and linor currents

To realize this model of linear induction motor we need to split the currents of primary and secondary in the d-q axis into two portions, the first portion is free from the end effects, and the second portion depending on end effects. by this method, the first portion works as a conventional induction motor(IM) current and the second portion is a weakening function caused by the linear induction motor end effects. To drive these currents, moreover, the flux linkages are also divided into two parts, the first is free from the end effects and will be specified by index "1", while the seconds labels the flux linkage dependent on the end effects, specified by index "2" .these fluxes are given by the following equations.

$$\lambda_{ds} = \lambda_{ds1} + +\lambda_{ds2} \quad (22)$$
$$\lambda_{qs} = \lambda_{qs1} + \lambda_{qs2} \quad (23)$$
$$\lambda_{dr} = \lambda_{dr1} + \lambda_{dr2} \quad (24)$$
$$\lambda_{qr} = \lambda_{qr1} + \lambda_{qr2} \quad (25)$$

Introducing equations from (22) to (25) into (16) to (19) and after some mathematical actions, the resulting equations appear:

$$i_{ds} = i_{ds1} + i_{ds2} \quad (26)$$
$$i_{qr} = i_{qr1} + i_{qr2} \quad (27)$$
$$i_{dr} = i_{dr1} + i_{dr2} \quad (28)$$
$$i_{qr} = i_{qr1} + i_{qr2} \quad (29)$$

When,

$$i_{ds1} = \frac{L_r\lambda_{ds1} - L_m\lambda_{dr1}}{L_\sigma} \quad (30)$$
$$i_{dr1} = \frac{L_s\lambda_{dr1} - L_m\lambda_{ds1}}{L_\sigma} \quad (31)$$
$$i_{qs1} = \frac{L_r\lambda_{qs1} - L_m\lambda_{qr1}}{L_\sigma} \quad (32)$$
$$i_{qr1} = \frac{L_s\lambda_{qr1} - L_m\lambda_{qs1}}{L_\sigma} \quad (33)$$

The component "2" can be found by subtracting the "1" component from the whole current.

The thrust force of linear induction motor can be separated into two parts, where the first part is analogous in definition to the thrust force of traditional IM and denoted by index"1", whereas the second part characterizes the weakening produced by the end effect and labeled by index"2". Thus, the total thrust for linear induction motor with end effect is given by:

$$F_e = F_{e1} + F_{e2} \quad (34)$$

The part that is analogous to the thrust force of a traditional IM is specified as:

$$F_{e1} = \frac{3\pi p}{2\tau_p 2}\left(\lambda_{ds1} i_{qs1} - \lambda_{qs1} i_{ds1}\right) \quad (35)$$

The thrust F_{e2} that weakens the original thrust that results as a result of end effect is specified by:

$$F_{e2} = F_{e2a} - F_{e2b} \quad (36)$$
$$F_{e2a} = \frac{3\pi p}{2\tau_p 2}\left(\lambda_{ds1} i_{qs2} + \lambda_{ds2} i_{qs1} + \lambda_{ds2} i_{qs2}\right) \quad (37)$$
$$F_{e2b} = \frac{3\pi p}{2\tau_p 2}\left(-\lambda_{qs1} i_{ds2} - \lambda_{qs2} i_{ds1} - \lambda_{qs2} i_{ds2}\right) \quad (38)$$

According to the above equations, we can find the dynamic model of LIM by built these equations in Simulink.

3. Simulation Model of Lim

The Simulink model of the two models of LIM considering the end effects is displayed in figure 3 and figure 5, whereas the internal construction of each model is shown in figure 4 and figure 6 using a synchronous reference frame where ω is considered as 314 rad/sec. The d-q model of LIM needs d-q axis input voltage names V_d, V_q; this can be achieved by transforming a 3-phase voltage $V_a, V_b, and\ V_c$ into 2-phase voltage $V_d and\ V_q$ via the park's transformation.

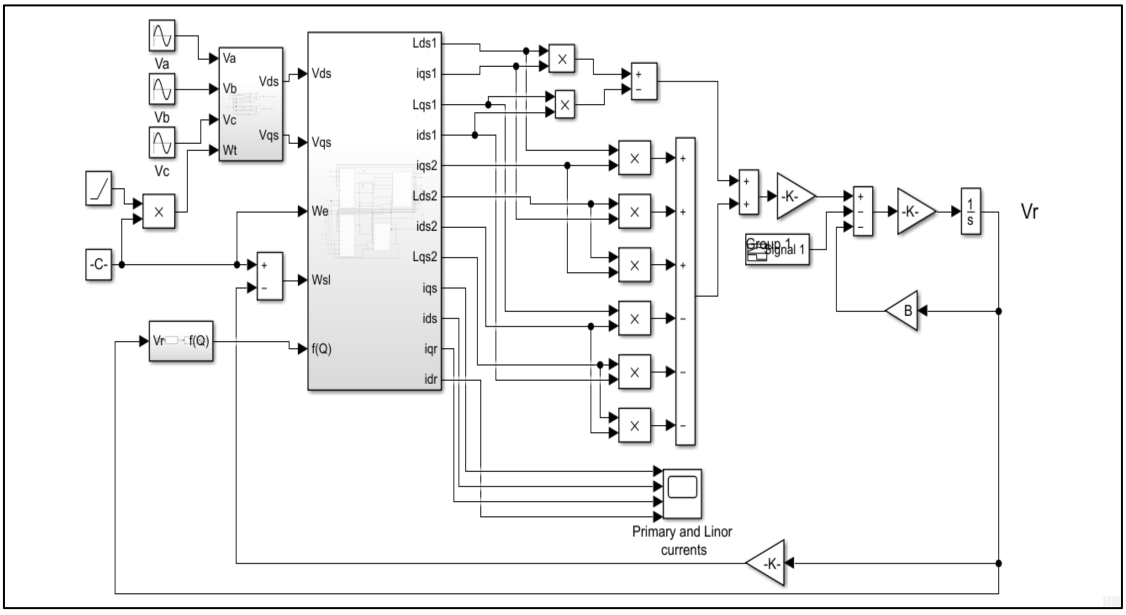

Fig.3 LIM model with separating currents.

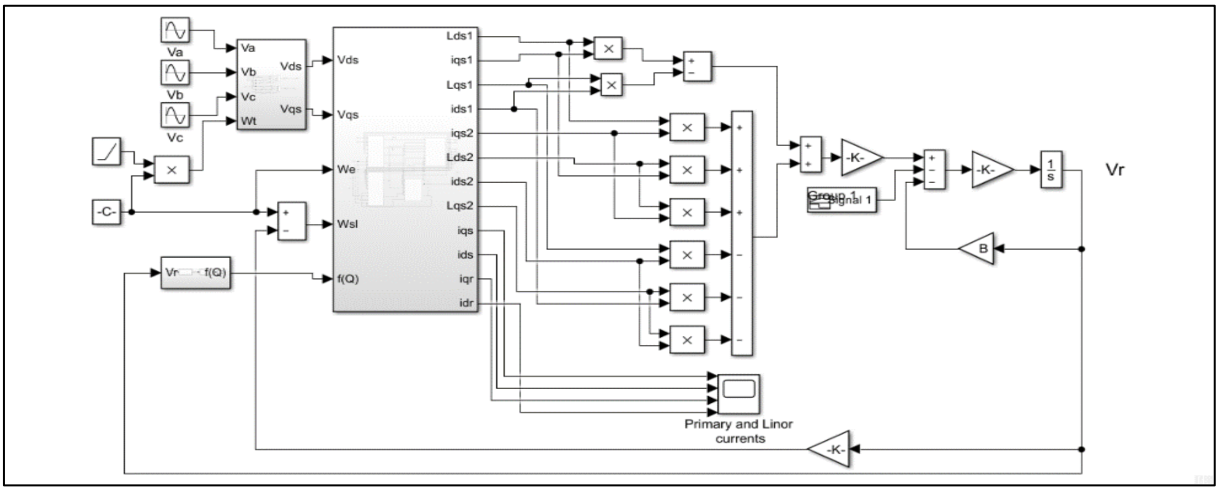

Fig.3 LIM model with separating currents.

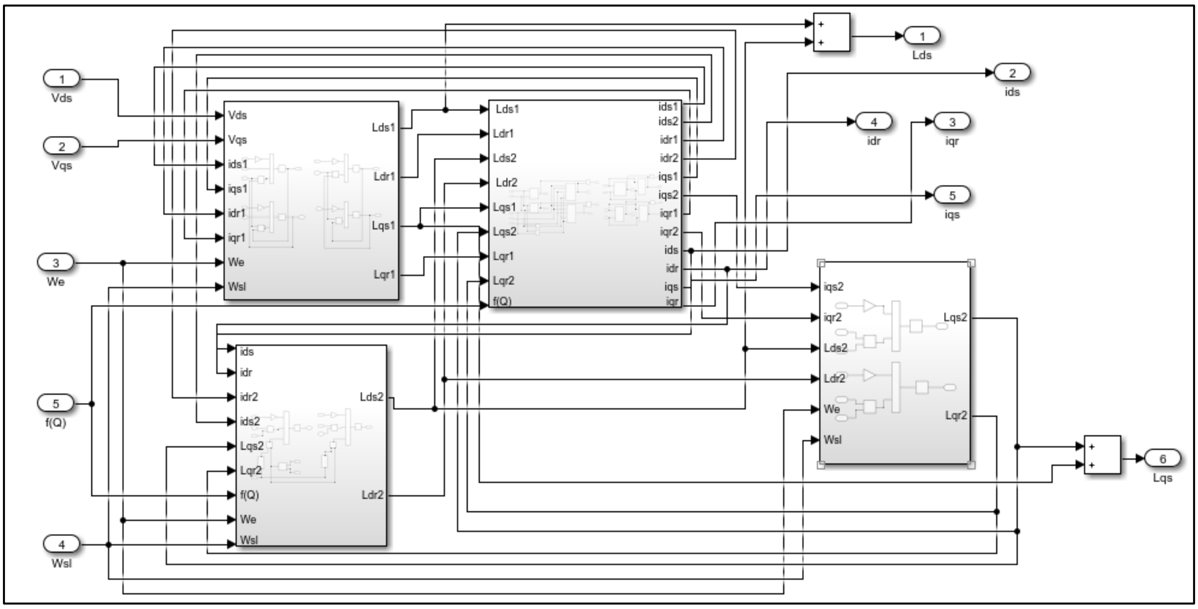

Fig.4 Internal construction of LIM model with separating currents

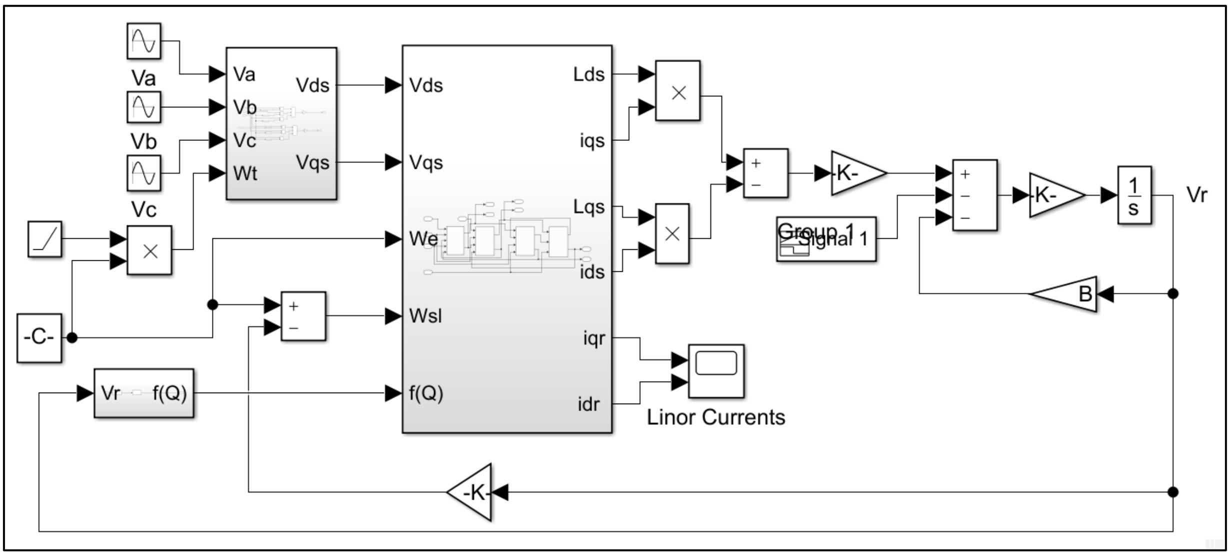

Fig.5 LIM model without separating currents

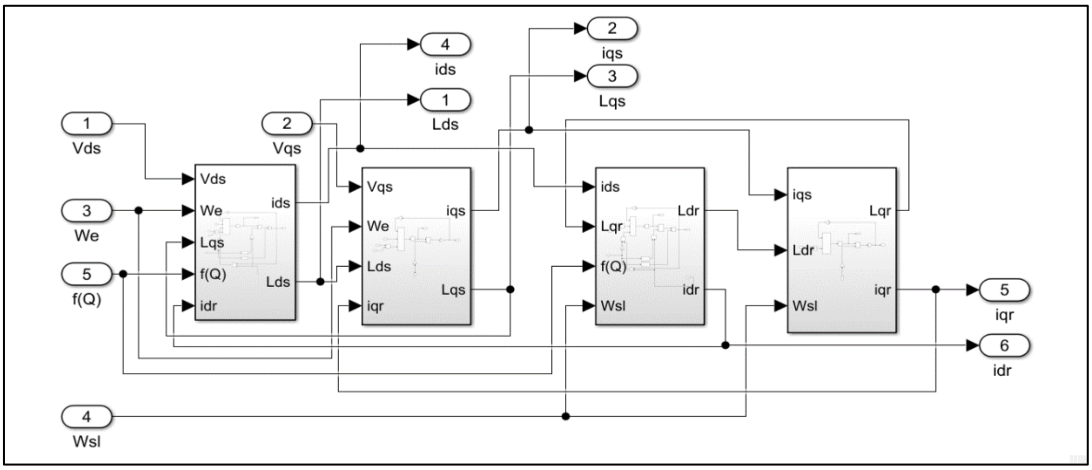

Fig.6 Internal Construction of LIM Model Without Separating Currents

Table 1: parameters used in the linear induction motor model

S. No	Parameters	values
1	P	4
2	τ_p (m)	0.0465
3	$R_s(\Omega)$	13.2
4	$R_r(\Omega)$	11.78
5	$L_s(H)$	0.42
6	$L_r(H)$	0.42
7	$L_m(H)$	0.4
8	M(kg)	4.775
9	B(kg/m)	53

4. Transformation techniques

The 3-phase magnitudes $V_a, V_b, and\ V_c$ are transformed to 2-phase magnitudes specifically $V_\alpha\ and\ V_\beta$ by Clark's transformation in a stationary reference frame. $V_\alpha\ and\ V_\beta$ is transformed to 2-phase orthogonal quantities namely $V_d\ and\ V_q$ in the rotating reference frame using the park's transformation.

The matrix that converts the 3-phase to 2-phase is defined as:

$$\begin{bmatrix}V_d\\V_q\\V_0\end{bmatrix}\frac{2}{3}\begin{bmatrix}\cos\omega t & \cos\left(\omega t-\frac{2\pi}{3}\right) & \cos\left(\omega t-\frac{4\pi}{3}\right)\\ -\sin\omega t & -\sin\left(\omega t-\frac{2\pi}{3}\right) & -\sin\left(\omega t-\frac{4\pi}{3}\right)\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix} \quad (39)$$

5. Simulation Results

The two models of linear induction motor are simulated for a step-change in load force of 200 N for a time from o.5 sec to 0.7 sec. The responses were obtained for thrust force, velocity, primary, and secondary d-q axis currents.

The velocity and thrust force for linear induction motor for the first model without separating currents are Shown in figure 7, while the velocity and the thrust force of LIM with separating currents are shown in figure 8.

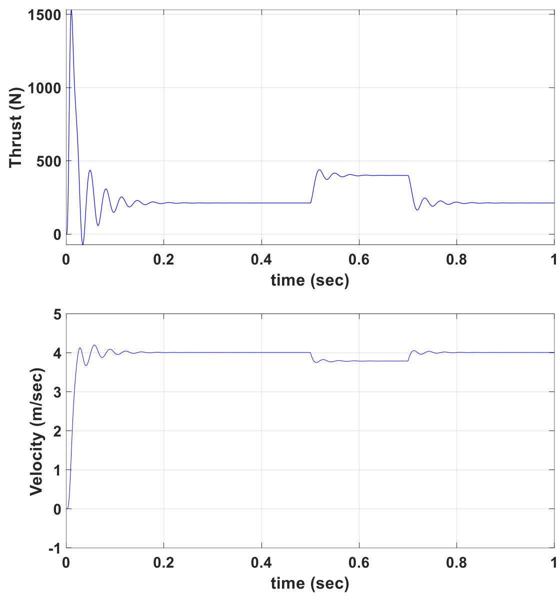

Fig.7 velocity and thrust force of the LIM model without separating currents.

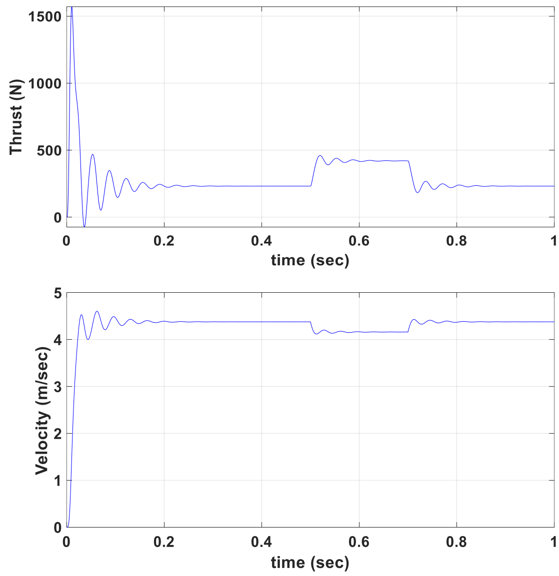

Fig.8 velocity and thrust force of the LIM model with separating currents.

The primary thrust is 1530 N for the linear induction motor model without separating primary and secondary d-q currents, while 1571 N for the LIM model with separating d-q primary and secondary currents. This drop is caused by the weakening thrust due to end effects that are bigger in the case of the LIM model without separating currents. As well as the velocity of the LIM model without separating currents is 4 m/sec whereas the speed of the second model is 4.37 m/sec. At 0.5 sec due to a load force of 200 N, the thrust force is increased while the velocity is reduced. After 0.7 sec, the LIM runs at the rated speed.

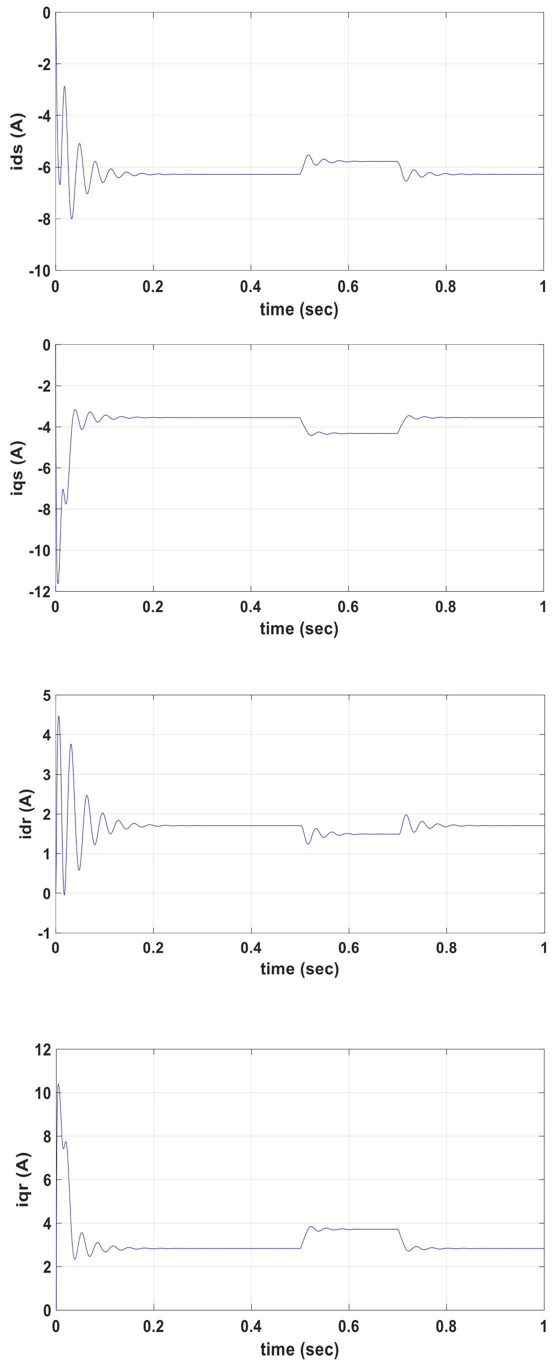

Fig.9 Primary and secondary d-q axis currents of LIM without splitting current.

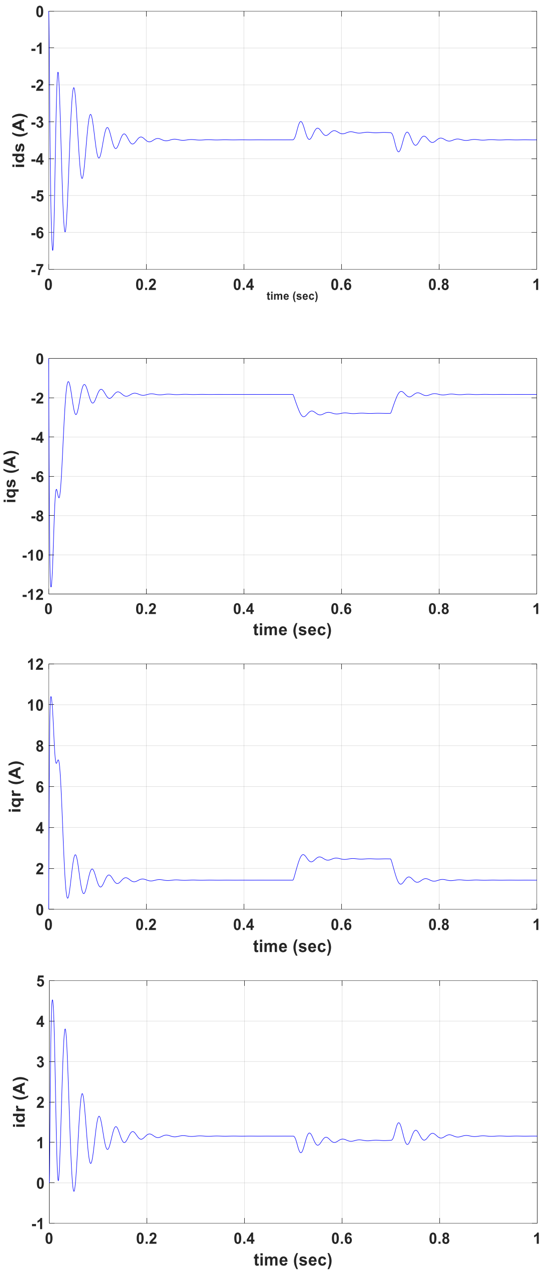

Fig.10 Primary and secondary d-q axis currents of LIM with splitting currents.

As presented in the results obtained for currents in figure 9 and figure 10, the currents in the case of separating primary and secondary d-q currents are better than currents in the case of do not separate it, because it is reached rated value better than another model, though the LIM model without splitting currents has less ripple compared with the second model.

Conclusion

In this work, the performance of linear induction motor for two different dynamic models considering end effects using a synchronous reference frame is studied and the results are compared. From the outcomes achieved it was decided that the dynamic model of LIM with splitting the primary and secondary d-q currents is better than the dynamic model of LIM without splitting currents in case of the thrust force and speed. But LIM model without splitting currents has less ripple compared to the second model.

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