A New Approach to Vector Control of Double-Sided Linear Induction Motors for Testing Aircraft and Submarine Models

Abdolamir Nekoubin
Islamic Azad University Natanz Branch

Abstract. One of applications of double sided linear induction motor is for investigating about aerodynamic conditions of aircraft and submarine hydrodynamic conditions, instead of real size model, models with smaller size can be moved with appropriate speed by linear induction motor above the water surface or inside of the water channel test. As a special and distinct feature, the linear induction motor generates attractive force between the primary and secondary members in addition to the propulsive force, which brake the motion during accelerating as well as imposes the control problem owing to the coupled flux and motion dynamics with the advantage of reducing the possibility of derailment. In this paper, the flux and motion dynamics for independent control of attraction and propulsion force is decoupled. This control strategy allows high performance to be achieved from linear induction motor.

Keywords: Independent Control, Attractive Force, Linear motors, Motion Dynamics

1. Introduction

The driving principles of the linear motor are similar to the traditional rotary induction motor (RIM), but its control characteristics are more complicated than the RIM, and the motor parameters are time varying due to the change of operating conditions, such as speed of mover, temperature[1]-[2]. Field-oriented control (FOC) or vector control of induction machines achieves decoupled torque and flux dynamics leading to independent control of the torque and flux with the same performance as achieved by separately excited DC machines[3]-[4]. The linear electric motors can be classified into following: DC motors, induction motors, synchronous motors and stepping motors etc. Among these, the linear induction motor (LIM) has many advantages such as reduction of mechanical losses and the size of motion devices, silence, high starting thrust force, and easy maintenance, repairing, and replacement [5]-[6]. Linear motors are electrical machines which unlike normal machines do not have rotors in the traditional sense, but elements which move in a straight line when the machine is excited [7]. In a normal three phase induction motor, the stator produces a rotating magnetic field which induces the rotor to rotate along with it. One may consider the Linear Induction Motor (LIM) to be constructed out of its rotary counterpart where the stator and the rotor have been cut and unrolled. Now, the stator produces a traveling magnetic field instead of a rotating one. The rotor is induced to move along it [8]-[9]. The exciting element of the LIM (like the stator in the normal rotary machine) is called the primary and the element in which currents are induced (like the rotor in the normal rotary machine) is called the secondary of the LIM. Usually either of the primary or the secondary is stationary and extends over the entire range of motion of the other element. Thus, LIMs may be classified as either short-primary (also called short-stator in literature) or short-secondary (called short-rotor) LIMs. LIMs may also be classified based on its construction as primary and one secondary placed one on top of the other, Double Sided LIM (DLIM) in which there are two primaries on the two sides of a secondary. They are also classified as high-speed and low-speed LIMs [10]-[11]-[12]. The basic difference in the analysis of the rotary induction motor and the LIM lies in the open air gap of the LIM due to the finite length and width of the
elements of the LIM. These cause pronounced 'distortions' called longitudinal and transverse end effects (due to the finite length and width respectively) [12].

The product of efficiency and power factor in a LIM usually does not exceed 0.5, whereas rotary induction motors with power factor= 0.8 have been designed. The reason why linear motors are preferred over normal motors for high speed propulsion is the fact that rotary motor propulsion depends on friction and is limited by the maximum achievable friction. The linear motor obtains its thrust from the traveling magnetic field, and thus, there is no theoretical limit to the maximum thrust achievable. This results in faster accelerations and higher speeds. Linear motors suggest themselves in low speed applications too where gearing mechanisms are preferably avoided [13]-[14]. In this paper, a double sided linear induction motor is controlled independently which it uses for testing models. For reducing the cost of equipments of flying or floating device, rather large sample test model, a smaller size model for analyzing their behavior can be used. For investigating about aerodynamic conditions of aircraft and submarine hydrodynamic conditions, instead of real size model, models with smaller size can be moved with appropriate speed by linear induction motor above the water surface or inside of the water channel test. This type of test as shown in fig.3, the speed of linear motor reaches 15 meters per second after the 70 meters distance(Positive acceleration), and for another 30 meters distance linear motor moves the model at a constant speed of 15 meters per second for testing models. The problems associated with the speed control of the linear induction motor and the rotary induction motors are approximately the same [15]. As a special and distinct feature, the linear induction motor produces vertical force, which is the force of attraction between the primary and secondary members in addition to propulsion force [16]. The propulsion force control features in the linear induction motor are almost the same as those of torque control features in the rotary induction motors [17]. It is only the attraction force, which requires special attention in case of linear induction motor while this attraction force cancels out in case of rotary induction motor. In spite of braking the motion and imposing the control problem, the Attraction force provides stability on track, ability to negotiate steeper and sharper turns, reduction in braking time (Ground transportation) etc[18]-[19]. The possible solution to the above mentioned problem is that the attraction force and the propulsion force must be controlled independently. The independent control feature provides ability to keep the attraction force at low value during acceleration to reduce settling time and energy consumption and to a high value during braking or at speed restricted areas so that it adds to the actual load between wheel and the rail, thereby increasing the resultant load and hence reduces the braking time for bringing the vehicle to rest or when passing through speed restricted areas [20]. The independent or decoupled control is possible through implementation of vector controller, which consists of three PI controllers and incorporates the features of phase and reference frame transformation. Generalized d-q modeling of linear induction motor simulated and validated for 20KW, 400V, 18A LIM Model at Electrical Machines and Drives Laboratory.

2. Modeling of DSLIM

The mathematical modeling of linear induction motor in d-q form is given by the following equations:

\[
\frac{dl_{ds}}{dt} = \left( \frac{R_s}{L_s} + 1 - \frac{6}{L_s} \right) l_{ds} + \frac{l_m}{L_s} \lambda_{dr} - \frac{l_m}{L_s} \lambda_{qr} + \frac{1}{L_s} V_{ds}
\] (1)

\[
\frac{dl_{qs}}{dt} = \left( \frac{R_s}{L_s} + 1 - \frac{6}{L_s} \right) l_{qs} + \frac{l_m}{L_s} \lambda_{qr} + \frac{l_m}{L_s} \lambda_{dr} + \frac{1}{L_s} V_{qs}
\] (2)

\[
\frac{dl_{dr}}{dt} = \frac{l_m}{L_r} l_{ds} - \frac{1}{\tau_r} \lambda_{dr} - \frac{\pi}{\tau_p} V_{qr}
\] (3)

\[
\frac{dl_{qr}}{dt} = \frac{l_m}{L_r} l_{qs} - \frac{1}{\tau_r} \lambda_{qr} - \frac{\pi}{\tau_p} V_{dr}
\] (4)

The propulsion force $F_t$, and attraction force $F_a$ developed by the linear induction motor, in terms of secondary flux and primary currents is given by the following equation:
\[
F_t = \frac{3}{2} P \left( \frac{L_m}{L_r} \right) \frac{\pi}{r_p} (I_{ds} \lambda_{qr} - I_{qs} \lambda_{dr}) \quad (5)
\]

\[
F_a = \frac{3}{4} P \left( \frac{L_m}{L_r} \right) (\lambda_{dr} I_{ds} + \lambda_{qr} I_{qs}) \quad (6)
\]

The mechanical equation, balancing the propulsion force with the fiction force, external load force and the accelerating force is given by the following equation:

\[
F_t = M_a \frac{dV}{dt} + BV + F_L \quad (7)
\]

The above equations 1-4 can he expressed in the following Matrix form:

\[
\begin{bmatrix}
\frac{d}{dt} q_s \\
\frac{d}{dt} q_r \\
\frac{d}{dt} r_s \\
\frac{d}{dt} r_p
\end{bmatrix} =
\begin{bmatrix}
\frac{\lambda_m}{L_s} & \frac{1 - \frac{6}{L_s}}{L_s} & 0 & 0 \\
0 & \frac{\lambda_m}{L_s} & \frac{1 - \frac{6}{L_s}}{L_s} & 0 \\
0 & 0 & \frac{\lambda_m}{L_s} & \frac{1 - \frac{6}{L_s}}{L_s} \\
0 & 0 & 0 & 1/L_r
\end{bmatrix}
\begin{bmatrix}
q_s \\
q_r \\
r_s \\
r_p
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{d}{dt} q_s \\
\frac{d}{dt} q_r \\
\frac{d}{dt} r_s \\
\frac{d}{dt} r_p
\end{bmatrix} =
\begin{bmatrix}
\frac{\lambda_m}{L_s} & \frac{1 - \frac{6}{L_s}}{L_s} & 0 & 0 \\
0 & \frac{\lambda_m}{L_s} & \frac{1 - \frac{6}{L_s}}{L_s} & 0 \\
0 & 0 & \frac{\lambda_m}{L_s} & \frac{1 - \frac{6}{L_s}}{L_s} \\
0 & 0 & 0 & 1/L_r
\end{bmatrix}
\begin{bmatrix}
q_s \\
q_r \\
r_s \\
r_p
\end{bmatrix}
\]

This matrix (Equation-8) has three parts, primary voltage as the input to the linear induction motor and primary current & secondary flux along with linear speed as the outputs. At the left hand side of the equation (8), the derivative part of the output has been shown, that has been separated for integration to get the outputs. The first two matrixes at the right hand side of equation (8) are forming two feedback loops. The modeling has been solved easily in Matlab/Simulink environment as it has powerful matrix and in built integration function. The outputs of the model have been further utilized for control purpose to the controllers to compare with the reference signals forming feedback Loops. Now, the propulsion force can be calculated from equation (5).

### 3. Decoupled Control of Linear Induction Motor

The LIM considered for analysis here is the double-sided primary, long-sheet-secondary as shown in fig1 and fig2.
The main objective of the paper is to achieve the decoupled control of the attraction force & the propulsion in linear induction motor drive. This is achieved by separating the secondary flux dynamics with the motion dynamics of the linear induction motor drive, which is done by using a d-q rotating reference frame synchronously with the secondary flux space vector and PI controllers for the control of secondary flux, linear speed, and propulsion force similar to those of rotor flux, rotational speed and torque controllers in case of rotary induction motor drives.

The principle behind the decoupled control is to split the primary current into two components, one is known as direct axis current component \( I_{ds} \) and another is the quadrature axis current component \( I_{qs} \). The direct axis primary current component \( I_{ds} \) is responsible for the production of the flux, also called magnetizing current component and the quadrature axis current component \( I_{qs} \) is responsible for the production of the thrust or propulsion force. These two primary current components are the hue control signals for the linear induction motor. In the proposed control scheme, the control signal \( I_{ds} \) is generated from the secondary flux controller and \( I_{qs} \) is generated from the successive outputs of the speed and the thrust controllers. The current components \( I_{ds} \) and \( I_{qs} \) are responsible for the production of the attraction force and propulsion force respectively. The independent control of these two current components serves the objective of achieving the desired decoupled control, which is obtained by the optimum setting of the parameters of the PI controllers. The \( \alpha-\beta \) stationary reference frame variables are obtained from the corresponding rotating reference frame d-q variables through an appropriate transformation involving secondary flux space vector angle. This transformation is given by:

\[
\begin{bmatrix}
\alpha \\
\beta
\end{bmatrix} =
\begin{bmatrix}
\cos(\theta) & -\sin(\theta) \\
\sin(\theta) & \cos(\theta)
\end{bmatrix}
\begin{bmatrix}
x_d \\
x_q
\end{bmatrix}
\]

4. Model Simulation and Results

The motor main parameter is shown in table I

<table>
<thead>
<tr>
<th>Components ( R_s )</th>
<th>Part name</th>
<th>Rating values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_s ) Primary Length</td>
<td>Primary Length</td>
<td>6.5 ( \Omega )</td>
</tr>
<tr>
<td>( R_r ) Secondary Length</td>
<td>Secondary Length</td>
<td>3.84 ( \Omega )</td>
</tr>
<tr>
<td>( L_s ) Number of pole</td>
<td>Number of pole</td>
<td>0.06H</td>
</tr>
<tr>
<td>( L_r ) Number of Slot</td>
<td>Number of Slot</td>
<td>0.055H</td>
</tr>
<tr>
<td>( \tau_p ) Pole pitch</td>
<td>Pole pitch</td>
<td>0.1209m</td>
</tr>
<tr>
<td>( f ) Line voltage</td>
<td>Line voltage</td>
<td>400volt</td>
</tr>
<tr>
<td>( f ) frequency</td>
<td>frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>( P_m ) Nominal output power</td>
<td>Nominal output power</td>
<td>20kw</td>
</tr>
</tbody>
</table>
For the linear speed, the parameters of the PI controller are desired on the basis of the rotor electrical and mechanical equations [20]. Figures 4-15 give the performance of the implemented decoupled controller for linear induction motor. Figures 6&11 show the attraction force Vs time curves for reference flux command of 0.5 & 1wb respectively. It is clear that the attraction force is constant for a fixed value of the reference input flux command. Although initially it overshoots, but within a very small period of time it settles at a steady value. Thus, keeping the flux at a fixed value, the attraction force between the primary and secondary members of the linear induction motor can be kept constant either at low value or high value depending upon the value of flux command. Also, it is clear from figures 9&14 that with large value of attraction force, the response time is large and it is small for small value of attraction force when considered as a load acting vertically and added to the mass to be accelerated or transported and braking the motion of the drive. Hence, the response is faster when the attraction force is kept low. Also, the thrust requirement increases with the increase in the attraction force acting as a load to track the reference speed.

Fig. 4. Linear speed Vs time characteristic for ref. flux Command of 0.5 wb and ref. speed command of 15 m/s Neglecting the effect of attraction force

Fig. 6. Attraction force Vs time characteristic for ref. flux Command of 0.5 wb

Fig. 5. Propulsion force Vs time characteristic for ref. flux Command of 0.5 wb and ref. speed command of 15 m/s Neglecting the effect of attraction force

Fig. 7. Characteristic of Id Vs time for linear induction motor

Fig. 8. Characteristic of Iq Vs time for linear induction motor
Fig. 9. Linear speed Vs time characteristic for ref. flux Command of 0.5 wb and ref. speed command of 15 m/s Accounting the effect of attraction force

Fig. 10. Propulsion force Vs time characteristic for ref. flux Command of 0.5 wb and ref. speed command of 15 m/s Accounting the effect of attraction force

Fig. 11. Attraction force Vs time characteristic for ref. flux Command of 1 wb

Fig. 12. Characteristic of Id Vs time for linear induction motor

Fig. 13. Characteristic of Iq Vs time for linear induction motor

Fig. 14. Linear speed Vs time characteristic for ref. flux Command of 1 wb and ref. speed command of 15 m/s Accounting the effect of attraction force
5. Conclusion

The linear induction motor generates attractive force between the primary and secondary members in addition to the propulsive force, which brake the motion during accelerating as well as imposes the control problem owing to the coupled flux and motion dynamics with the advantage of reducing the possibility of derailment. The purpose of decoupled control is to keep the attraction force at starting (during acceleration) at low value and to keep it at high value during deceleration to lower the value of the response time in both the cases i.e.in order to achieve fast response of the drive. The simulation results of the proposed control scheme using three PI controllers are satisfactory. The speed, flux and thrust PI regulators have been successfully implemented.

6. References


Abdolamir Nekoubin was born in Iran, in 1985. He received the B.S. degree in 2007 and the M.S. degree in 2009, all in electrical engineering from Islamic Azad University, Najaf Abad Branch. His current research interests include induction motor, linear induction motor, and nonlinear control theory. Currently he is member of young researchers club.