Parameter estimation of three-phase linear induction motor by a DSP-based electric-drives system

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ABSTRACT

This work describes a method to characterize a three-phase linear induction motor in order to determine the various parameters used in its per-phase equivalent circuit by a DSP-based electric-drives system. In LIM (Linear Induction Motor), the air gap is very large compared with the RIMs (Rotary Induction Motors). Further, the secondary part normally does not have slotted structure. It is just made of aluminum and steel plates. Therefore, the effective air gap is larger than the physical air gap. High air gap makes a larger leakage inductance. It leads to lower efficiency and lower power factor. DC resistance test will be done to determine the value of Rs. The primary Inductance Ls will be calculated by running the LIM at synchronous speed. The secondary parameters i.e. Llr and Rr' will be calculated by blocked-mover test. The experiment for no load test is shown and include a DC motor coupled to the LIM under test. Two methods to calculate the secondary parameters are described.

Keywords:
Parameters estimation
Linear induction motor
DSP-based electric-drives
Per-phase equivalent circuit

1. INTRODUCTION

Although the linear motor was invented and patented more than a century ago, in the beginning it was impractical due to the difficulty of having a small air gap without roughness and with low power factor efficiency. However, technological advances have given the linear induction motor (LIM) greater importance at the academic and industrial levels, and its use has been extended in many applications [1-5]. Before the advent of linear motors, rotary motors with rotational-to-linear motion converters and with full mechanical transmissions were used to produce straight line movement. Using linear motors for applications that require linear motion eliminates gears and other mechanisms. The advantages of LIMs applied to linear movement are, among others, high capacity to perform acceleration and deceleration, ability to work in hostile environments, gears and mechanical transmissions are avoided, great ease of control of thrust and speed, existence of normal forces that can be used in levitation, low maintenance cost, low noise, great versatility in negotiating sharp curves and steep slopes, ability to exert force on the secondary without mechanical contact, movement and braking independent of the terrain, and low pollution [6-12].

The Lab-Volt Model 8228-02 is a Single Side Linear Induction Motor (SLIM) [13-15]. The stator is composed of a three-legged laminated iron core upon which are mounted three identical coils A, B, C. Each coil has 500 turns of No. 21 AWG copper wire, with a tap at 300 turns. The coils produce in each leg and corresponding salient pole, fluxes that are labeled \( \phi_a \), \( \phi_b \) and \( \phi_c \). These fluxes are created by the currents...
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2. EXPERIMENT DESIGN

The system for the speed of a DC motor and velocity and position of the LIM is shown in Figure 2. The encoder signal (speed and position of LIM motor) is fed back to the DS1104 board via CP1104 [23]. The $i_v$ phase-current and $dA$ duty cycle quantities are required to estimation of the LIM parameters. In the experiment, a Simulink model of a two pole DC switch-mode power converter will be built to control the voltage of the DC motor in real-time. The two-pole switch-mode DC converter voltage is the difference between the individual pole-voltages of the two-switching power-poles in Figure 3. The average output voltage $\bar{v}_{ab}$ can range from to $+V_{DC}$ and $-V_{DC}$ depending on the individual average pole voltages.

![Figure 3. Two pole DC switch-mode power converter](image)

To achieve both positive and negative values of $v_{ab}$, a common-mode voltage equal in magnitude to $V_{DC}/2$ is injected in the individual pole-voltages. The pole-voltages are then given by:

$$dA = \frac{1}{2} + \frac{1}{2} V_{DC} dB = \frac{1}{2} - \frac{1}{2} V_{DC}$$

(2)

The above equation was implemented in Simulink. $dA$ governs the duty cycle of the $S1$ switch PWM and $dB$ governs the duty cycle of the $S2$ switch PWM. Like was made earlier the PWM device was configured for center aligned PWM. Which forces symmetry about the center of the period. This configuration produces two pulses line-to-line during each period. The effective switching frequency is doubled, reducing the ripple current while not increasing the switching losses in the Power Electronics Drive Board.

A three-phase balanced voltage source of variable magnitude and frequency is required, to run the linear induction motor at synchronous frequency. The duty ratios for the three poles A, B and C to generate this type of voltage source are given by [24]:

$$d_a(t) = \frac{1}{2} + \frac{1}{2} V_m \cos(\omega t)$$

$$d_b(t) = \frac{1}{2} - \frac{1}{2} V_{dim}$$

$$d_c(t) = \frac{1}{2} - \frac{1}{2} V_m \cos(\omega t - 4\pi/3)$$

(3)

In (4) are modified form of (3) given in [24] which are suitable for real-time implementation.

$$d_a(t) = 0.5 + 0.5u[1] \cos(u[2])$$

$$d_b(t) = 0.5 + 0.5u[1] \cos(u[2] - 2\pi/3)$$

$$d_c(t) = 0.5 + 0.5u[1] \cos(u[2] - 4\pi/3)$$

(4)

where

$$u[2] = 2\pi ft = \left(\frac{1}{s}\right) 2\pi$$

$$s \rightarrow Laplace\ Operator$$

$$u[1] = \frac{V_m}{V_{dim}}$$

(5)
There are various aspects to take into account in the experiment realization. One difficulty associated with the LIM is that due to the limit in the LIM stroke, it is not easy to make a high speed no-load condition which is need for primary winding inductance estimation. To avoid such difficulty, we are considering to apply a lower frequency than the nominal frequency, and move the LIM in back and forth by DC motor at corresponding synchronous speed controlling its direction via the LIM position. The LIM movement is restricted between 0 cm and 10 cm. To avoid sudden changes of reference speed in the motor a first order filter has been added. Sudden changes can cause high current peaks. In order to measure the LIM position and velocity the speedmeasured2 simulink block was made. The linear encoder has a resolution of 20 μm per channel thus the linear position may be in millimeters dividing the encoder counter value by 50. It has a two quadrature channels, thus the accuracy is 5 μm. The control-desk panel for run the experiment is shown in Figure 4. The control-desk panel allow us to set the DC motor speed, LIM position limits and LIM frequency and monitors the duty cycles and LIM velocity in real-time.

![Control desk panel](image)

Figure 4. Control desk panel

To achieve no-load condition the LIM is feed with a lower frequency than rather frequency and via DC motor the system is moved at corresponding synchronous velocity. Since the secondary part of the LIM does not have slotted structure, the secondary leakage inductance is much smaller than the primary leakage inductance. Because of this, many parameter estimation methods of the RIM are not applicable to the LIM [25]. The mutual inductance $L_m$ will be calculated by solving a third order polynomial which will be derived from the total equivalent inductance [25]. Such method of obtaining $L_m$ directly allow us to calculate the leakage inductances of the primary and secondary windings separately and the secondary resistance.

3. PRIMARY INDUCTANCE AND RESISTANCE ESTIMATION

Primary resistance may be estimated by DC current test. Applying constant line-line voltages $V_{uv}, V_{vw}, V_{wu}$, we can get generate DC phase currents. Then, we obtain:

\[
R_{s1} = \frac{R_{uv}}{2} = \frac{V_{uv}}{1I_u} = 1.6865 \Omega \\
R_{s2} = \frac{R_{uw}}{2} = \frac{V_{uw}}{1I_v} = 1.6680 \Omega
\]
\[ R_{s3} = \frac{R_{wu}}{2} = \frac{V_{wu}}{I_{wu}} = 1,6900\Omega \]

Primary resistance is the average of \( R_{s1}, R_{s2} \) and \( R_{s3} \)

\[ R_s = 1,6875\Omega \]

In estimating the primary inductance \( L_s \), the secondary circuit should be seen as little as possible. To isolate the effects of the secondary circuit it is necessary to minimize the slip moving LIM at synchronous speed by DC motor. Then the LIM load is reduced. To reduce end effect, frequency \( f = \frac{\omega_e}{2\pi} \) needs to be selected less than 18Hz, since end effect is negligibly small for \( f < 18Hz \) [26, 27]. Under no load or a low slip condition, we can obtain from the Figure 1 an approximate equation such that:

\[ v_s = R_s i_s + j\omega_e L_s i_s \]

Multiplying by \( i_s \) and dividing by 2 both sides of before equation we obtain:

\[ \frac{v_s i_s}{2} = \frac{R_s i_s^2}{2} + j\omega_e L_s i_s^2 \]

\[ V_{sym} i_{sym} = R_s i_{sym}^2 + j\omega_e L_s i_{sym}^2 \]

\[ S = P + jQ \]

where \( L_s = L_{ls} + L_m \), \( \omega_e \) is the exiting angular frequency, \( P \) is the active power and \( Q \) is the reactive power.

The experiment was made increasing the referen- ce frequency for the linear induction machine (by \textit{ref-Vel-LIM/Value} slider in the Control-Desk panel) to 3Hz corresponding frequency of the synchronous velocity and slowly increasing the DC motor speed to LIM mechanical synchronous velocity dictated by (1) (by \textit{ref-Vel-DC/Value} slider in the Control-Desk panel), we obtained the LIM performance depicted in Figure 5 with \( V_s = 0.549m/s \). The \( V/F \) ratio and LIM stroke limit was settled in 300V/20Hz and 100cm respectively.

![Figure 5. LIM mover velocity with no-load condition](image)

Taking the waveforms for dA and iv on the oscilloscope as shown in Figure 6, we obtain the readings for the rms values of these variables. Also, we measure the phase difference between the two waveforms using the cursors.
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Figure 6. $V_a$ and $I_a$ wave forms with no-load condition

$$d_{A,rms} = 0.053033$$
$$i_{A,rms} = 0.5356$$
$$Phase = \frac{35}{333.33} \cdot 360^\circ = \theta = 37.8^\circ$$

The scaling factor for $d_A$ and $i_v$ are 10 and 0.125 respectively. Actual rms values of the phase $v$ voltage, phase $i$ current and the per phase reactive power drawn by the three-phase linear induction motor can be calculated as follows:

$$v_{v,rms} = \frac{d_{A,rms} \cdot 300V}{10} = d_{A,rms} \text{(measured on the scope)} \cdot \frac{300V}{10} = 15.9099V$$
$$i_{v,rms} = \frac{i_{v,rms} \text{(measured)}}{0.125} = 4.2851A$$
$$Q = i_{v,rms}v_{v,rms} \sin \theta = 41.7852VAR$$

Where $\cos \theta$ is the displacement power factor.

This reactive power is consumed by primary inductance $L_s$ thus:

$$Q = \omega_L L_i i_{v,rms}^2$$

$L_s$ can be calculated from the above equation.

$$L_s = \frac{Q}{\omega_L i_{v,rms}^2} = \frac{v_{v,rms} i_{v,rms} \sin \theta}{\omega_L i_{v,rms}^2} = \frac{v_{v,rms} \sin \theta}{\omega_L v_{v,rms}} = 120,7256mH$$
4. ESTIMATION OF $R_{eq}$ AND $L_{eq}$

For obtaining the mutual $L_{m}$ and secondary inductances $L_{r}$, a large current must flow through the secondary circuit, i.e., current path through the secondary circuit must be dominant. To provide a large current flow through the secondary circuit, the mover-locked test is used. Since at standstill $v_x = 0$ (mover velocity), the LIM equivalent circuit shown in Figure 7 can be represented as a series circuit, such that:

$$ Z_{eq} = R_{eq} + j\omega_e L_{eq} $$

(6)

$R_{eq}$ and $L_{eq}$ denote the total resistance and the total inductance and need to be estimated to obtain the estimates of the secondary parameters.

For $i_s(t) = I_s \sin(\omega_e t)$, the $v_s(t)$ voltage is obtained in the steady state, such that:

$$ v_s(t) = R_{eq}i_s(t) + j\omega_e L_{eq}i_s(t) $$

(7)

Multiplying by $i_s(t)$ and dividing by 2 both sides of before equation we obtain:

$$ v_{s_{rms}}^2 = R_{eq}^2 i_{s_{rms}}^2(t) + j\omega_e L_{eq}i_{s_{rms}}^2(t) $$

$$ S = P + jQ $$

where $\omega_e$ is the exiting angular frequency, $P$ is the active power and $Q$ is the reactive power.

The experiment was made increasing the reference frequency for the linear induction machine (by ref-Vel-LIM/Value slider in the Control-Desk panel) to 30Hz and locked the LIM mover. The $V/F$ ratio and LIM stroke limit was settled in 300V/60Hz and 100cm respectively. In the Figure 8 the experiment result is shown.

Figure 8. $V_a$ and $I_a$ wave forms in blocked-mover test
The active power is \( P = R_{eq} i_{rms}^2 = v_{rms} i_{rms} \cos \theta = 53VA \), and the reactive power \( Q = \omega_e L_{eq} i_{rms}^2 = v_i \sin \theta = 112,6469\text{VAR} \) where \( \theta = \arctan \frac{\omega_e L_{eq}}{R_{eq}} \) then,

\[
R_{eq} = \frac{P}{i_{rms}^2} = 9.62\Omega \\
L_{eq} = \frac{R_{eq}}{\omega_e i_{rms}^2} = 108,4721mH
\]

5. ESTIMATION OF \( L_m, L_r, \) AND \( R_r \) FROM A THIRD-ORDER POLYNOMIAL

Utilizing the estimated values, we define \( \delta_l = L_s - L_{eq} \). We let \( \beta = \frac{\tan \omega}{L_{eq}} \), which is unknown. Choosing \( \omega_e \) high enough so that \( R_s^2 \ll \omega_e L_r^2 \), one can approximate \( R_{eq} \) and \( L_{eq} \) from the circuit of the Figure 7 such that:

\[
R_{eq} \approx R_s + \frac{L_s^2}{L_r} R_r = R_s + \beta^2 R_r \tag{8}
\]

\[
L_{eq} \approx L_{ls} + \frac{L_m}{L_r} L_{lr} = L_{ls} + \beta L_{lr} \tag{9}
\]

Since \( L_s = L_m + L_{ls}, L_r = L_m + L_{lr} \) and \( L_{eq} \approx L_{ls} + \beta L_{lr} \), it follows that

\[
L_{ls} = L_s + L_m \tag{10}
\]

\[
L_{lr} = \frac{L_m - \delta_l}{\beta} \tag{11}
\]

\[
L_r = \frac{(1 + \beta) L_m - \delta_l}{\beta} \tag{12}
\]

\[
R_r = \frac{R_{eq} - R_s}{\beta^2} \tag{13}
\]

Note that \( L_m \) is the only unknown value in the above definitions. Substituting (10), (11), (12), and (13) into \( L_{eq} \) from the circuit of the Figure 7, we obtain a third-order polynomial for \( L_m \), such that:

\[
L_m^3 + AL_m^2 + BL_m + C = 0 \tag{14}
\]

where \( A = -(1 + \beta) \delta_l \beta - \delta_l/(1 + \beta), B = 2 \delta_l^2 / \beta, C = -\delta_l^2 / \beta (1 + \beta) - \beta \delta_l R_r^2 / \omega_e^2 (1 + \beta) \). Note again that the coefficients \( A, B, \) and \( C \) are available with the methods suggested above. The numerical solution of (14) is found by the solve function of MATLAB®.

Once \( L_m \) is found, the estimates \( L_{ls}, L_{lr}, L_r, \) and \( R_r \) are obtained directly from (10) to (13), respectively. \( R_r \) is an intermediate estimate needed for deriving polynomial (14). Based on the estimates \( L_m \) and \( L_r \), we have a more accurate estimation method for \( R_r \) than (14). Rearranging \( R_{eq} \) in Figure 7, we obtain (15). The LIM parameters are shown in Table 1.

\[
R_r = \frac{(\omega_e L_m)^2 - (\omega_e L_m)^4 - (2 \omega_e L_{lr} (R_{eq} - R_s))^2}{2 (R_{eq} - R_s)} \tag{15}
\]

<table>
<thead>
<tr>
<th>Table 1. LIM parameters</th>
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<tbody>
<tr>
<td>( R_s = 1.6974 \Omega )</td>
</tr>
<tr>
<td>( L_s = 0.1207H )</td>
</tr>
<tr>
<td>( R_{eq} = 9.6200 \Omega )</td>
</tr>
<tr>
<td>( L_{eq} = 0.1085H )</td>
</tr>
<tr>
<td>( R_r = 9.3720 \Omega )</td>
</tr>
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</table>

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6. ESTIMATION OF $L_m$, $L_r$, AND $R_e$ FROM A THE EQUATION SYSTEM

Knowing that $L_s = L_{ls} + L_m$, $L_r = L_{lr} + L_m$ and, substituting $L_{ls}$ and $L_{lr}$ into equation in Figure 7, the follow equation system is obtained:

$$\begin{align*}
R_{eq} &= R_e + \frac{\omega L_{eq} R_e}{R_e^2 + \omega^2 L_{eq}^2} \\
L_{eq} &= L_s - L_m + \frac{l_m [\beta + \omega L_{eq} (L_s - L_m)]}{R_e^2 + \omega^2 L_{eq}^2} \\
\frac{L_m}{L_r} &= \beta \Rightarrow L_r = \frac{L_m}{\beta}
\end{align*} \tag{16}$$

Since $L_m$ and $L_r$ are unknown, $\beta$ is also not known, it is around 0.95 in rotary induction motors, and 0.9 in linear induction motors. Giving a value to $\beta$, between 0.9 and 0.95, the unknown variables are $L_m$, $R_e$, and $L_r$.

Solving the system of the (16). The LIM parameters are showed in Table 2.

<table>
<thead>
<tr>
<th>Table 2. LIM parameters</th>
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<tbody>
<tr>
<td>$R_e = 1.6875 , \Omega$</td>
</tr>
<tr>
<td>$L_m = 0.1370 , \Omega$</td>
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<tr>
<td>$L_s = 0.1207 , \Omega$</td>
</tr>
<tr>
<td>$R_{eq} = 9.6200 , \Omega$</td>
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<tr>
<td>$L_{eq} = 0.1085 , \Omega$</td>
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<tr>
<td>$L_r = 0.1666 , \Omega$</td>
</tr>
<tr>
<td>$R_e = 1.1666 , \Omega$</td>
</tr>
<tr>
<td>$R_{eq,adj} = 10.1666 , \Omega$</td>
</tr>
</tbody>
</table>

7. CONCLUSION

The electric parameters for a linear induction motor were determined in two ways. This parameters constitute the equivalent per phase electric circuit of LIM. The experiment for no-load and locked-mover test were designed using a DSP-based electric-drives system with two motors coupled, a DC Machine and a LIM. The control programs were made using MATLAB-Simulink of Matworks and Control-Desk of dSPACE. Adjustable Speed Driver was developed in the Universidad Nacional de Colombia - Manizales for the LIM control.

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