

# Parameter Estimation of Linear Induction Motor LabVolt 8228-02

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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 (Kang *et al.*, 2003). DC resistance test will be done to determine the value of  $R_s$ . The primary inductance  $L_s$  will be calculated by running the LIM at synchronous speed. The secondary parameters i.e.  $L_{lr}$  and  $R_r'$  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.

**Index Terms:** Parameters Estimation , Linear Induction Motor, DSP-based electric-drives, per-phase equivalent circuit.

## I. INTRODUCTION

The Lab-Volt Model 8228-02 is a Single Side Linear Induction Motor (SLIM). 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  $i_a$ ,  $i_b$  and  $i_c$  that flow in the respective windings; consequently, the fluxes are  $120^\circ$  out of phase. This phase shift means that the fluxes attain their maximum value at different times, separated by intervals of  $\frac{1}{3f}$  where  $f$  is the frequency of the source. If the phase sequence is A-B-C, flux  $\phi_b$  will attain its maximum value  $\frac{1}{3f}$  s after  $\phi_a$ . Similarly,  $\phi_c$  will reach its maximum value  $\frac{1}{3f}$  s after  $\phi_b$ . Then, the flux continually shifts from left to right across the face of the salient poles. If two of the

supply lines are interchanged, the phase sequence will reverse, and the flux will shift from right to left across the poles.

Knowing the distance  $d$  between the center of the poles, we can calculate the speed at which the flux moves. This is called the synchronous speed  $v_s$  because it is directly related to the frequency of the power supply. The synchronous speed is given by

$$v_s = 3df \quad (1)$$

in the Model 8228,  $d = 0,061m$ .

In this paper a three-phase linear induction motor will be characterized to determine the various parameters used in its per-phase equivalent circuit (Fig. 1) by a DSP-based electric-drives system. The experiment is shown in Fig. 2, where a DC motor is coupled to the LIM under test.

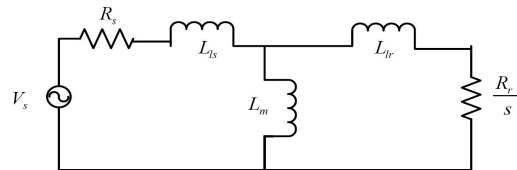


Figure 1. Per-phase equivalent circuit of a three-phase induction motor.

There are five major components of the DSP-based electric-drives system, which will be used to perform the experiment. They are as follows: 1) Motor coupling system, 2) Power Electronics Drive Board, 3) Adjustable speed driver (ASD), 4) DSP based DS1104 R&D controller card and CP 1104 I/O board and 5) MATLAB Simulink and Control-desk.

1. **Motor coupling system:** This system contains the LIM that needs to be characterized. The system has

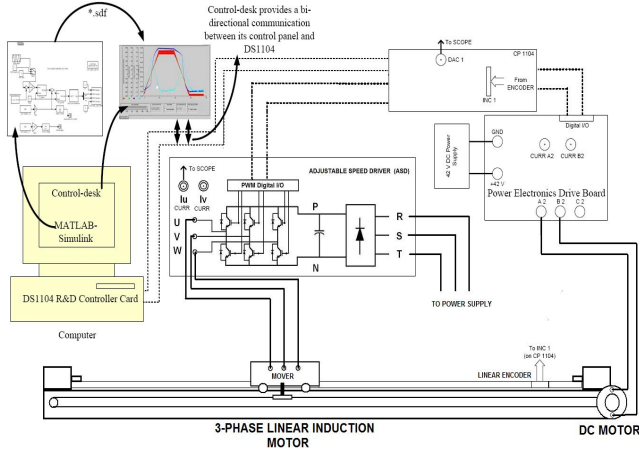


Figure 2. Experiment for LIM parameter identification.

a mechanical coupling arrangement to couple LIM and DC motors. The system also has a linear encoder mounted which is used to measure the position and the speed of the LIM. The motors demand controlled pulse-width-modulated (PWM) voltages to run at controlled speed. The PWM voltages are generated by Power Electronics Drive Board and Adjustable speed driver (subsequently described); the voltage sources thus generated are connected to the motor coupling system as shown in Fig. 2.

2. **Power Electronics Drive Board:** This board has the capability to generate two independent PWM voltage sources (A1B1C1 and A2B2C2) from a constant DC voltage source. Hence two machines can be controlled independently for independent control variables, at the same time. In this experiment we will use only one PWM voltage source (A2B2C2) to control the DC motor speed. To generate the controlled PWM voltage source, this board requires various digital control signals. These control signals dictates the magnitude of the PWM voltage source. They are generated by the DS1104 R&D Controller board inside the computer.
3. **Adjustable Speed Driver (ASD):** This board has the capability to generate PWM voltage source (UVW) from a 3-phase voltage source. Hence LIM can be controlled independently for independent control variables. To generate the controlled PWM voltage source, this board requires various digital control signals. These control signals dictates the magnitude and phase of the PWM voltage source. They are generated by the DS1104 R&D Controller board.
4. **DS1104 R&D controller Board and CP 1104 I/O board:** In each discrete-time-step, the DS1104 controller board takes some action to generate the digital control signals. The type of action is governed in this board with the help of MATLAB-Simulink real-time interface. This board monitors the input (i.e. motor

current, speed, voltage etc) with the help of CP1104 I/O board in each discrete-time step. Based on the inputs and the variables that need to be controlled; it takes the programmed action to generate the controlled digital signals. The CP1104 I/O board is an input-output interface board among the Power Electronics Drive Board, Adjustable Speed Driver and DS1104 controller board. It takes the motor current, dc-voltage etc. from the Power Electronics Drive Board and Adjustable Speed Driver also, speed signal (from linear encoder) from motor coupling system, to the DS1104 controller board. In turn, the controlled digital signals supplied by DS1104 controller board are driven to the Power Electronics Drive Board and Adjustable Speed Driver by CP1104.

5. **MATLAB Simulink and Control-desk (Programming DS1104 and control in realtime):** The I/O ports of CP 1104 are accessible from inside the Simulink library browser. Creating a program in Simulink and procedure to use the I/O port of CP 1104 will be detailed in this experiment. When you build the Simulink control-system (CTRL+B) by using real-time option, it implements the whole system inside the DSP of DS1104 board, i.e. the controlsystem that is in software (Simulink) gets converted into a real-time system on hardware (DS1104). Simulink generates a \*.sdf file when you build (CTRL+B) the control-system. This file gives access to the variables of controlsystem (like reference speed, gain, tuning the controller etc) to separate software called Control-desk. In this software a control panel (see Fig. 4) can be created that can change the variables of control-system in real time to communicate with DS1104 and hence change the reference quantities such as the DC motor speed, LIM frequency, V/f ratio and LIM stroke limit ( $t_{ope}$ ) by sliders or numeric entries.

## II. EXPERIMENT DESIGN

The system for the speed of a DC motor and velocity and position of the LIM is shown in Fig. 2. The encoder signal (speed and position of LIM motor) is fed back to the DS1104 board via CP 1104. 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 (Fig. 3). The average output voltage  $\bar{v}_{ab}$  can range from to  $+V_{DC}$  and  $-V_{DC}$  depending on the individual average pole voltages.

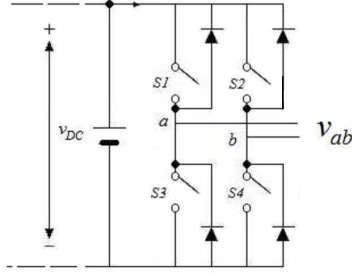


Figure 3. Two pole DC switch-mode power converter.

To achieve both positive and negative values of  $\bar{v}_{ab}$ , 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:

$$dA = \frac{1}{2} + \frac{1}{2} \frac{\bar{v}_{ab}}{V_{DC}} dB = \frac{1}{2} - \frac{1}{2} \frac{\bar{v}_{ab}}{V_{DC}}$$

The above equations 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 (section 4-6- 2(Mohan, 2001)):

$$\begin{aligned} d_a(t) &= \frac{1}{2} + \frac{1}{2} \frac{v_{m,A}(t)}{V_{dlim}}; v_{m,A}(t) = V_m \cos(\omega t) \\ d_b(t) &= \frac{1}{2} - \frac{1}{2} \frac{v_{m,B}(t)}{V_{dlim}}; v_{m,B}(t) = V_m \cos(\omega t - 2\pi/3) \\ d_c(t) &= \frac{1}{2} - \frac{1}{2} \frac{v_{m,C}(t)}{V_{dlim}}; v_{m,C}(t) = V_m \cos(\omega t - 4\pi/3) \end{aligned} \quad (2)$$

Equations (3) are modified form of equations (2) given in (Mohan, 2001) which are suitable for real-time implementation.

$$\begin{aligned} d_a(t) &= 0,5 + \frac{1}{2} u[1] \cos(u[2]); \\ d_b(t) &= 0,5 + \frac{1}{2} u[1] \cos(u[2] - 2\pi/3); \\ d_c(t) &= 0,5 + \frac{1}{2} u[1] \cos(u[2] - 4\pi/3); \end{aligned} \quad (3)$$

Where

$$\begin{aligned} u[2] &= 2\pi ft = \left(\frac{1}{s} f\right) 2\pi; \\ s &\rightarrow \text{Laplace Operator}; \\ u[1] &= \frac{V_m}{V_{dlim}} \end{aligned}$$

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, 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  $t_{ope}$  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 speedmeasuredc2 simulink block was made. The linear encoder has a resolution of  $20\mu\text{m}$  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  $5\mu\text{m}$ .

The control-desk panel for run the experiment is shown in Fig. 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.

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.

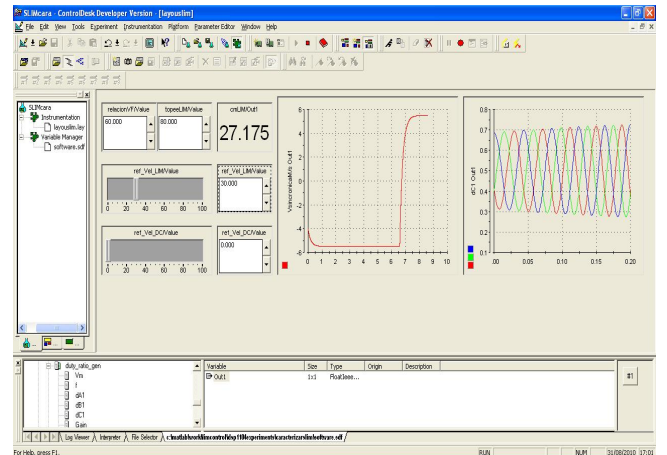


Figure 4. Control Desk Panel.

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 (Kang *et al.*, 2001).

The mutual inductance  $L_m$  will be calculated by solving a third order polynomial which will be derived from the total equivalent inductance (Kang *et al.*, 2001). 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.

### III. 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

$$\begin{aligned} R_{s1} &= \frac{R_{uv}}{2} = \frac{V_{uv}}{2I_u} = 1,6865\Omega \\ R_{s2} &= \frac{R_{vw}}{2} = \frac{V_{vw}}{2I_v} = 1,6680\Omega \\ R_{s3} &= \frac{R_{wu}}{2} = \frac{V_{wu}}{2I_w} = 1,6900\Omega \end{aligned}$$

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  $f = \omega_e/2\pi$  needs to be selected less than 18 Hz, since end effect is negligibly small for  $f < 18$  Hz (Gieras *et al.*, 1987; Gieras, 1994).

Under no load or a low slip condition, we can obtain from the Fig. 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

$$\begin{aligned} \frac{V_s i_s}{2} &= \frac{R_s i_s^2}{2} + j \frac{\omega_e L_s i_s^2}{2} \\ V_{s_{rms}} i_{s_{rms}} &= R_s i_{s_{rms}}^2 + j\omega_e L_s i_{s_{rms}}^2 \\ S &= P + jQ \end{aligned}$$

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 reference frequency for the linear induction machine (by ref-Vel-LIM/Value slider in the Control-Desk panel) to 3 Hz corresponding frequency of the synchronous velocity and slowly increasing the DC motor speed to LIM mechanical synchronous velocity dictated by (1) (by ref-Vel-DC/Value slider in the Control-Desk panel), we obtained the LIM performance depicted in Fig. 5 with  $V_s = 0,549m/s$ . The V/F ratio and LIM stroke limit was settled in 300V/20Hz and 100cm respectively.

Taking the waveforms for  $d_A$  and  $i_v$  on the oscilloscope

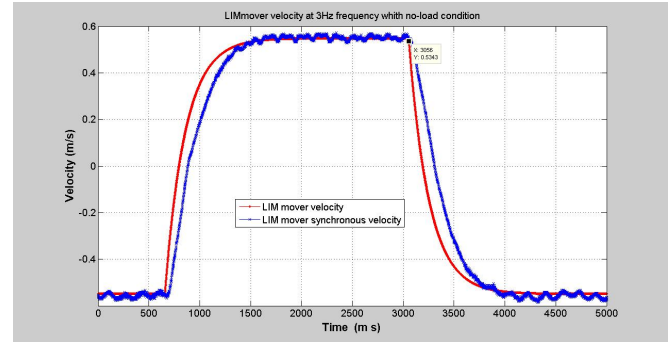


Figure 5. LIM mover velocity with no-load condition

(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.

$$\begin{aligned} d_{A,rms} &= 0,053033 \\ I_{A,rms} &= 0,5356 \\ Phase &= \frac{35}{333,33} 360^\circ = \theta = 37,8^\circ \end{aligned}$$

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

$$\begin{aligned} v_{v,rms} &= d_{A,rms} 300V \\ &= \frac{d_{A,rms}(\text{measured on the scope})}{10} 300V \\ &= 15,9099V \\ i_{v,rms} &= \frac{i_{v,rms}(\text{measured})}{0,125} = 4,2851A \\ Q &= v_{v,rms} i_{v,rms} \sin\theta = 41,7852VAR \end{aligned}$$

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

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

$$Q = \omega_e L_s i_{v,rms}^2$$

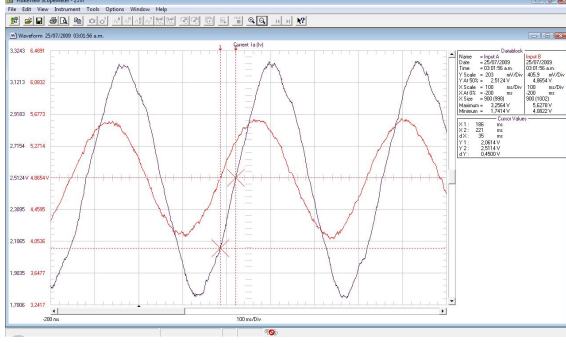


Figure 6. Va and Ia wave forms with no-load condition

$L_s$  can be calculated from the above equation.

$$L_s = \frac{Q}{\omega_e i_{v,rms}^2}$$

$$L_s = \frac{v_{v,rms} i_{v,rms} \sin\theta}{\omega_e i_{v,rms}^2}$$

$$L_s = \frac{v_{v,rms} \sin\theta}{\omega_e i_{v,rms}}$$

Then

$$L_s = 120,7256mH$$

#### IV. 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.

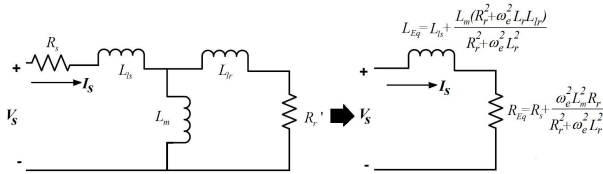


Figure 7. Equivalent circuit of a LIM at standstill.

Since at standstill  $v_x = 0$  (mover velocity), the LIM equivalent circuit shown in Fig. 7 can be represented as a series circuit, such that

$$Z_{eq} = R_{eq} + j\omega_e L_{eq} \quad (4)$$

where

$$R_{eq} = R_s + \frac{\omega_e^2 L_m^2 R_r}{R_r^2 + \omega_e^2 L_r^2} \quad (5)$$

$$L_{eq} = L_{ls} + \frac{L_m(R_r^2 + \omega_e^2 L_r L_{lr})}{R_r^2 + \omega_e^2 L_r^2} \quad (6)$$

$R_{eq}$  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

$$v_s(t) = R_{eq} i_s(t) + j\omega_e L_{eq} i_s(t) \quad (7)$$

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

$$v_{s,rms} i_{s,rms} = R_{eq} i_{s,rms}^2 + j\omega_e L_{eq} i_{s,rms}^2$$

$$S = P + jQ$$

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 30 Hz and locked the LIM mover. The V/F ratio and LIM stroke limit was settled in 300V/60Hz and 100cm respectively. In the Fig. 8 the experiment result is shown.

$$d_{A,rms} = 0,1768$$

$$I_{A,rms} = 0,2934$$

$$Phase = \frac{6}{33,33} 360^\circ = \theta = 64,8^\circ$$

The  $v_{v,rms}$  and  $i_{v,rms}$  values are:

$$v_{v,rms} = d_{A,rms} 300V$$

$$= \frac{d_{A,rms} (\text{measured on the scope})}{10} 300V$$

$$= 53,04V$$

$$i_{v,rms} = \frac{I_{A,rms} (\text{measured})}{0,125} = 2,3472A$$

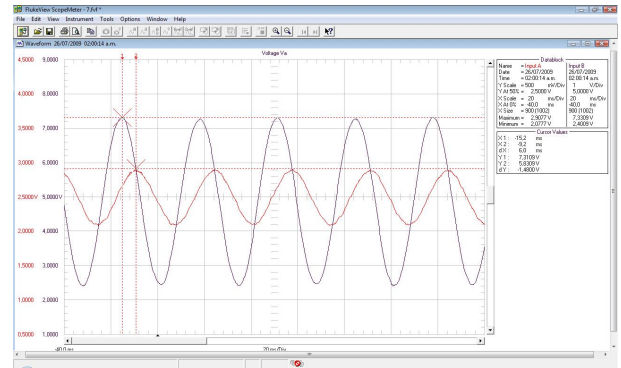


Figure 8. Va and Ia wave forms in blocked-mover test

The active power is  $P = R_{eq} i_{s,rms}^2 = v_{s,rms} i_{s,rms} \cos\theta = 53VA$ , and the reactive power  $Q = \omega_e L_{eq} i_{s,rms}^2 = v_{s,rms} i_{s,rms} \sin\theta = 112,6469VAR$  where  $\theta = \arctan \frac{\omega_e L_{eq}}{R_{eq}}$  then,

$$R_{eq} = \frac{P}{i_{s,rms}^2} = 9,62\Omega \quad (8)$$

and

$$L_{eq} = \frac{Q}{\omega_e i_{s, rms}^2} = 108,4721mH \quad (9)$$

### V. ESTIMATION OF $L_m$ , $L_r$ AND $R_r$ FROM A THIRD-ORDER POLYNOMIAL

Utilizing the estimated values, we define  $\delta_L = \hat{L}_s - L_{eq}$ . We let  $\beta = L_m/L_r$ , which is unknown. Choosing  $\omega_e$  high enough so that  $R_r^2 \ll \omega_e^2 L_r^2$ , one can approximate (5) and (4) such that

$$R_{eq} \approx R_s + \frac{L_m^2}{L_r^2} R_r = R_s + \beta^2 R_r \quad (10)$$

$$L_{eq} \approx L_{ls} + \frac{L_m}{L_r} L_{lr} = L_{ls} + \beta L_{lr} \quad (11)$$

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

$$L_{ls} = L_s - L_m \quad (12)$$

$$L_{lr} = \frac{L_m - \delta_l}{\beta} \quad (13)$$

$$L_r = \frac{(1 + \beta)L_m - \delta_L}{\beta} \quad (14)$$

$$R_r = \frac{R_{eq} - R_s}{\beta^2} \quad (15)$$

Note that  $L_m$  is the only unknown value in the above definitions. Substituting (12), (13), (14), and (15) into (6), we obtain a third-order polynomial for  $L_m$ , such that

$$L_m^3 + AL_m^2 + BL_m + C = 0 \quad (16)$$

where  $A = -(1 + \beta)\delta_L/\beta - \delta_L/(1 + \beta)$ ,  $B = 2\delta_L^2/\beta$ ,  $C = -\delta_L^3/\beta(1 + \beta) - \beta\delta_L R_r^2/\omega_e^2(1 + \beta)$ . Note again that the coefficients  $A$ ,  $B$ , and  $C$  are available with the methods suggested above. The numerical solution of (16) 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 (12) to (15), respectively.  $R_r$  is an intermediate estimate needed for deriving polynomial (16). Based on the estimates  $L_m$  and  $L_r$ , we have a more accurate estimation method for  $R_r$  than (15). Rearranging (5), we obtain (17)

$$R_r = \frac{(\omega_e L_m)^2 - \sqrt{(\omega_e L_m)^4 - (2\omega_e L_r (R_{eq} - R_s))^2}}{2(R_{eq} - R_s)} \quad (17)$$

Then the LIM parameters are:

$R_s = 1,6875\Omega$	$L_m = 0,0420H$
$L_s = 0,1207H$	$L_{ls} = 0,0788H$
$R_{eq} = 9,6200\Omega$	$L_{lr} = 0,0323H$
$L_{eq} = 0,1085H$	$L_r = 0,0743H$
$R_r = 9,3720\Omega$	$R_{r,adj} = 3,9444\Omega$

### VI. ESTIMATION OF $L_m$ , $L_r$ AND $R_r$ FROM 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 (6), the follow equation system is obtained:

$$\begin{aligned} R_{eq} &= R_s + \frac{\omega_e^2 L_m^2 R_r}{R_r^2 + \omega_e^2 L_r^2} \\ L_{eq} &= L_s - L_m + \frac{L_m [R_r^2 + \omega_e^2 L_r (L_r - L_m)]}{R_r^2 + \omega_e^2 L_r^2} \\ \frac{L_m}{L_r} &= \beta \Rightarrow L_r = \frac{L_m}{\beta} \end{aligned} \quad (18)$$

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  $L_m$ ,  $R_r$  and  $L_r$ .

Solving the system of the equation (18), the LIM parameters are:

$R_s = 1,6875\Omega$	$L_m = 0,1704H$
$L_s = 0,1207H$	$L_{ls} = -0,0497H$
$R_{eq} = 9,6200\Omega$	$L_{lr} = 0,0148H$
$L_{eq} = 0,1085H$	$L_r = 0,1852H$
$R_r = 10,1666\Omega$	$R_{r,adj} = 10,1666\Omega$

### VII. 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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